LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Department of Energy Technology
Section of Thermal and Environmental Engineering

ADVANCED CONTROL METHODS FOR REDUCING NITROGEN OXIDES IN A FLUIDIZED BED BOILER

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ABSTRACT

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The aim of this thesis was to reduce nitrogen oxides emissions of a fluidized bed boiler. As the emissions were already low thanks to fluidized bed combustion technology and hybrid SNCR/SCR nitrogen oxides abatement system, it was decided to decrease the emissions by improving the control of ammonia injection. The original ammonia injection control was too slow to prevent the nitrogen oxide peaks caused by occasional disturbances. Ammonia injection was improved by adding piston pumps to each ammonia line. Thus, the ammonia flow can be directed to the ammonia feeding points, where it is most needed. A new fuzzy logic based controller was developed for ammonia injection control. Other advanced control methods such as neural network were also utilized in the controller development. Ammonia injection controller was tested successfully at the power plant of Brista Kraft Ab in Märsta, Sweden.

TIIVISTELMÄ

Tekijä: Lintunen, Teija

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Tämän työn tarkoituksena oli löytää keinoja erään leijukerroskattilan typenoksidipäästöjen vähentämiseksi. Koska päästöt olivat jo alunperin alhaiset leijukerrostekniikan ja hybridin SNCR/SCR –typenpoistolaitteiston ansiosta, päätettiin päästöjä lähteä vähentämään parantamalla ammoniakkiruiskutuksen säätöä. Alkuperäinen ammoniakkiruiskutuksen säätö oli liian hidas, jotta satunnaisten häiriöiden aiheuttamat typenoksidipiikit olisi pystytty poistamaan. Ammoniakkiruiskutusta parannettiin lisäämällä jokaiseen ammoniakkilinjaan mäntäpumput, joiden avulla ammoniakkia voidaan syöttää sinne, missä sitä eniten tarvitaan. Ammoniakkiruiskutuksen säätöön kehitettiin uusi sumeaan logiikkaan perustuva säätäjä. Myös muita kehittyneitä säätömenetelmiä kuten neuroverkkoa hyödynnettiin säätäjän kehityksessä. Ammoniakkiruiskutuksen säätäjää testattiin menestyksekkäästi Ruotsissa Brista Kraftin Märstassa sijaitsevalla voimalaitoksella.

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Teija Lintunen

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NOMENCLATURE

a	parameter
A	constant in Arrhenius equation, 1/s
A	coefficient
A	price, SEK
b	parameter
B	coefficient
B	price, SEK
c	parameter
c	concentration, ppm, mg/Nm^3
C	price, SEK
d	parameter
E	activation energy, J/mol
J	criterion
$\bar{J}$	derivative of criterion
$\tilde{J}$	integrative of criterion
k	kinetic rate constant
K	equilibrium constant
m	mass, kg
$\dot{m}$	mass flow, kg/s
M	molar mass, kg/kmol
n	reaction order ,mol
n	length of the averaging period, s
$\dot{n}$	molar flow, mol/s
q_v	volume flow, m^3/s
Q	volume flow, m^3/s
Q	coefficient
p	pressure, Pa
R	universal gas constant, J/molK
R	coefficient

S	coefficient
t	time, s
T	temperature, K
$u(t)$	function
V_m	molar volume, mol/m^3
x	measured value
x'	moving average
$x(t)$	function
$\dot{x}(t)$	derivative of function
$	price, SEK/h

Subscripts

a	index
a	air
c	concentration
fg	flue gas
i	index
$+i$	kinetic
$-i$	thermodynamic
j	index
$meas$	measured
n	index
$prim$	primary
red	reduced
sec	secondary
$slip$	ammonia slip
$theor$	theoretical

Greek letters

β	exponent of Arrhenius equation
λ	stoichiometric air coefficient
φ	threshold, bias
φ	relative moisture, %
Δ	delta
Σ	summing junction

Acronyms

ANFIS	adaptive network based fuzzy inference system
BFB	bubbling fluidized bed
CFB	circulating fluidized bed
CFBC	circulating fluidized bed combustion
CHP	combined heat and power
CPU	central processing unit
CSTR	continuous stirred tank reactor
D	derivative
DCS	distributed control system
DOAS	differential optical absorption spectroscopy
EPA	Environmental Pollution Agency
ESP	electrostatic precipitator
FBC	fluidized bed combustion
FGD	flue gas desulphurization
FGR	flue gas recirculation
FTIR	fourier transform infra red
HHV	higher heating value
I	integrative
IEA	International Energy Agency
IR	infra red
LHV	lower heating value
LQ	linear quadratic
LQP	linear quadratic problem
MF	membership function
MPC	model predictive control
NDIR	non-dispersive infra red
NDUV	non-dispersive ultra violet
P	proportional
PCD	program change decision
PD	proportional derivative

PFR	plug flow reactor
PI	proportional integrative
PID	proportional integrative derivative
PLC	programmable logic controller
PPP	polluter pays principle
PSR	perfectly stirred reactor
SCR	selective catalytic reduction
SEK	Swedish crown
SNCR	selective non-catalytic reduction
UV	ultra violet
VIS	visible
VLSI	very large-scale integration

1. INTRODUCTION

1.1 Background

Nitrogen oxides are a group of gaseous pollutants, emissions of which are regulated by the authorities. Fluidized bed combustion is considered as a good method for preventing these emissions because of its lower combustion temperature and staged combustion method. NO_x emission level of 70 mg/MJ can be easily reached in biofuel-fired fluidized bed boilers without removing nitrogen oxides from flue gas. In Sweden, the annual NO_x emission limit is 70 mg/MJ. In addition to this, a so called Polluter Pays Principle (PPP) is applied there. This means that every kilogram of nitrogen oxides produced at the power plants has its price. Every Swedish power plant over 10 MW or producing annually at least 50 GWh must report the NO_x emissions. Emissions of the power plants are compared as kilograms per useful energy unit, and an average for the annual NO_x emission is calculated. Power plants emitting more NO_x than the annual average have to pay the nitrogen oxides charge, while the power plants where NO_x emission remains under the average will receive money from the nitrogen oxides charge. This has significantly shortened the repayment period of the investments on NO_x abatement.

Foster Wheeler Energia Oy has supplied the Brista Kraft Ab in Sweden with a circulating fluidized bed (CFB) boiler, which is equipped with a hybrid SNCR/SCR NO_x abatement. With the hybrid system, it is possible to reduce NO_x emissions up to 90 % while maintaining ammonia slip under 5 ppm. At the Brista Kraft Ab power plant, the guaranteed NO_x emission is 20 mg/MJ. In year 1998, the power plant was among the ten least polluting power plants in Sweden. In spite of this, the NO_x emissions can be further reduced. There has been made a conclusion that the NO_x peaks, which are formed during the disturbances in power plant process, increase the annual NO_x emission, and they must be reduced. Traditional ammonia injection control with a feedback from continuous NO_x emission measurement tends to be too slow to prevent the formation of nitrogen oxide peaks. Thus, the aim was to develop a new ammonia injection control concept, which is significantly faster than the old one, and which is capable of predicting the formation of NO_x peaks. If the NO_x emissions can be reduced, it will bring economical profit as well as strengthen the image of the power plant.

This Master's Thesis is a part of a development project realised at the Foster Wheeler Energia Oy, in Karhula R&D Center. The aim of this project is to reduce the NO_x emissions of the CFB boiler owned by Brista Kraft Ab by developing an adaptive intelligent controller based on fuzzy logic. The further goal is to minimize the nitrogen oxide emissions and to optimize the ammonia use. The controller is being developed in co-operation with Visi Systems Oy located in Karhula, Finland.

1.2 Aim of This Thesis

The aim of this thesis is to gather the information needed for the controller development. The information includes theory of NO_x formation in the fluidized bed combustion, theory of NO_x abatement and theory of applying the advanced control methods. Furthermore, the process values will be collected and studied. Some field tests are to be made with the modified ammonia injection system. In the frames of the field tests, some emission measurements will be done. The collected information will be used in the development of an adaptive, intelligent controller, which will be able to cut down the NO_x emission peaks. The performance of the new controller will be tested to prove that it functions better than the old one.

Meanwhile, the combustion process will be studied and the correlations between process values and NO_x emission will be tracked. The performance of the hybrid SNCR/SCR system will be evaluated. All this aims to the reduction of the NO_x emission at the Brista Kraft Ab power plant. The task is challenging, as the NO_x emissions are already low. The results of the development project are introduced at end of this Thesis. This study is restricted to biofuel-fired fluidized bed combustion.

2. EMISSIONS OF NITROGEN OXIDES

Nitrogen forms seven different oxides, which are nitrogen monoxide NO, nitrogen dioxide NO_2, nitrous oxide N_2O, N_2O_3, N_2O_4, N_2O_5 and NO_3. Relevant compounds in combustion are NO, NO_2 and N_2O. The amounts of other compounds formed in the combustion are negligible. (Helynen, 1992, pp. 58) NO and NO_2 are together referred as nitrogen oxides, NO_x. Nitrogen oxides react with water and oxygen in the atmosphere and form nitric acid. Nitric acid is together with the sulfuric acid a main contributor of acid rain. In general, NO reacts with oxygen to form NO_2. NO_2 is a brown gas, which is serious respiratory irritant. Nitrogen oxides are also one of the principle constituents of smog and harmful PM_{10} particles. N_2O has an interaction with the global warming and the ozone layer depletion. (De Nevers, 1995, s. 372-374)

2.1 Formation of Nitrogen Oxides

Nitrogen oxides are mainly formed in the motor traffic and in the combustion of fossil fuels. In the emission balance, natural sources must be considered as well. According to IEA, the main emission sources are human activities and natural sources. Human activities include the combustion of fossil fuels, the combustion of biomass and agricultural activities. Natural sources include lightning and microbial activity in the soil. Fossil fuels are being combusted in power plants, in road transport, in aircraft and in shipping. In some cases, the combustion of biomass is included in agricultural activities as well as the nitrogen-based fertilizing. The combustion of biomass includes deforestation, savanna fires, slash and burn agriculture, fuel-wood burning, natural forest fires and burning of agricultural wastes. While elevated nitrogen concentrations in the Northern Hemisphere are mostly due to human activities, lightning is the most important factor in nitrogen balance in the Southern Hemisphere. Emissions from the natural sources are estimated to be equivalent to one half or less than the emissions from human activities. It is estimated that 14 % of the world's population in North America and Europe causes around 70% of the total NO_x -emissions. (Sloss, 1998, pp. 7-10)

2.1.1 NO_x Emissions in Combustion

NO_x reactions in the combustion process produce mostly nitrogen monoxide NO (about 95 %) and only small amounts of nitrogen dioxide NO_2. Nevertheless, the total NO_x amount is defined as NO_2. The reason for this is that NO will convert to NO_2 relatively fast in the flue gas ducts, in the stack and in the atmosphere. Nitrogen oxides formed in the combustion process originate from the molecular nitrogen of the combustion air and from the small amounts of organically bound nitrogen in the fuel. The factors that influence on the NO reactions are fuel type, combustion temperature, amount of free radicals, amount of oxygen and the retention time in the combustion zone. Figure 1 presents the effect of temperature on the NO formation with the different types of formation mechanisms.

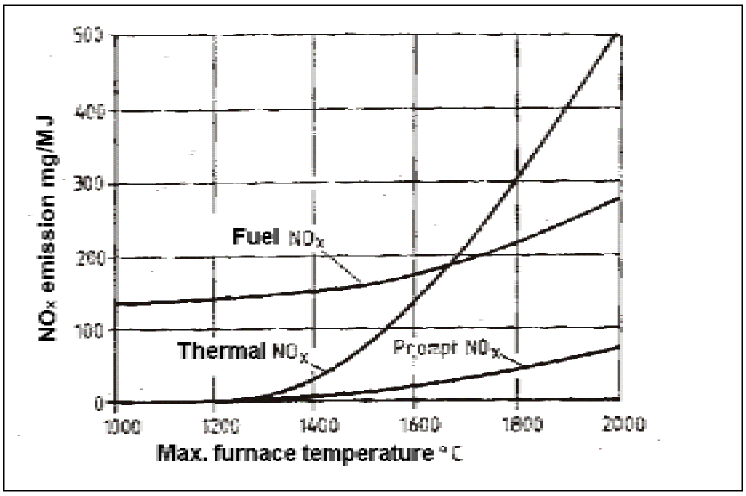


Figure 1. Effect of temperature on the NO emission of oil-fired boiler. (Huhtinen et al., 1994, pp. 84)

Because of the slow kinetics of the NO reactions, nitrogen oxide concentration is somewhat hundreds of ppm, although according to the equilibrium curve presented in Figure 2 it should be zero.

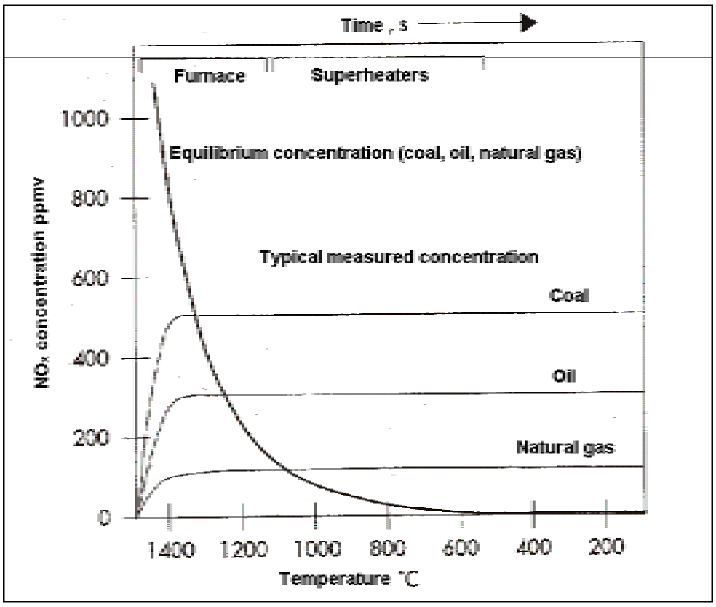


Figure 2. *Equilibrium curve of nitrogen monoxide and measured NO concentrations in pulverized coal-fired boiler, oil-fired boiler and natural gas-fired boiler without NO_x abatement equipment. (Kilpinen, 1995, pp. 241)*

In the low flue gas temperatures, the degradation reactions of NO are very slow, and the NO emission level reached in the combustion zone remains almost the same. (Kilpinen, 1995, pp. 239-242)

2.1.1.1 Thermal NO

Thermal NO is produced in the flame at high temperatures via a series of oxidation reactions called the Zeldovich mechanism. These reactions proceed by steps involving highly energetic particles called free radicals. The free radicals that are most often involved are O, N, OH, H and such hydrocarbons, which have lost one or more hydrogens like CH_3. Free radicals are very reactive, and they exist in significant concentrations only at high temperatures. (De Nevers, 1995, pp. 380) It is still uncertain, at which temperature these reactions take place, but they are accelerating when the flame temperature increases. It is estimated that these reactions are significant when the combustion temperature rises above 1700 K. In fluidized bed combustion, temperatures in the furnace are low enough to prevent the formation of thermal NO_x. (Helynen, 1992 pp. 60-61)

2.1.1.2 Prompt NO

Prompt NO occurs in the fuel rich combustion, where hydrocarbon radicals from fuel (mostly CH) react with atmospheric nitrogen. Hydrogen cyanide, HCN, has an important role in these reactions. Hydrocarbon radicals break atmospheric nitrogen molecules and form HCN, which reacts to nitrogen atoms. These single nitrogen atoms finally form the NO. The reaction time is very short, and when the reactions are finished no more NO will be produced. This reaction is significant only in the natural gas combustion, where large concentrations of hydrocarbon radicals are present. (Moreea-Taha, 2000, pp. 9)

2.1.1.3 Fuel NO

The fraction of the organically bound fuel nitrogen is minimal when it is compared to the amount of the atmospheric nitrogen, but the fuel nitrogen is very reactive, and it oxidizes very easily to NO. In normal combustion, 20-80 % from fuel nitrogen oxidizes to NO. Table 1 presents the nitrogen contents of the typical fuels.

Table 1. Nitrogen contents of the typical fuels. Nitrogen of the natural gas is not organically bound fuel nitrogen but molecule nitrogen, which behaves like atmospheric nitrogen. (Kilpinen, 1995, pp. 248)

Fuel	**Nitrogen content [w-% in d.s.]**
Petshora coal	2,2
Polish coal	1,0
Peat	1,7
Heavy fuel oil	0,7
Light fuel oil	0,2
Wood	0,5
Sulfite liquor	0,1
Black liquor	0,1
Natural gas	5,0

From Table 1, it can be seen that coal, peat and heavy fuel oil contain more fuel nitrogen and their NO_x emissions are significantly higher than those with less fuel bound nitrogen. Reactions, which form fuel NO, are not so well known than those of the other NO formation types. In fuel NO reactions, nitrogen compounds degrade to simpler molecules such as hydrogen cyanide HCN and ammonia NH_3. These reaction products are able to react further with the oxygen containing compounds to NO or with NO to molecule nitrogen. Which of these reactions will take place depends on the oxygen concentration. When oxygen concentration in the flame is high, the reaction to NO becomes dominant. (Helynen, 1992, pp. 62-63)

2.1.2 NO_x Emissions in Fluidized Bed Combustion

In fluidized bed boiler, combustion takes place in a particle layer, which contains sand, ash, char and possibly an additive. Particle layer is fluidized by the primary air, which is delivered underneath the bed. There are two main types of fluidized beds: bubbling fluidized bed and circulating fluidized bed. In bubbling fluidized bed, the fluidizing air velocity is between 1-3 m/s and particle free zone can be clearly observed. In circulating fluidized bed, fluidizing air velocity is about 5-10 m/s, and particle suspension is spread all over furnace. Particles will be separated from the flue gas with cyclone separator and returned to the furnace. (Kilpinen, 1995, pp. 257)

Basu and Fraser have defined circulating fluidized bed boiler as follows:

A circulating fluidized bed (CFB) boiler is a device for generating steam by burning fossil fuels in a furnace operated under a special hydrodynamic condition: where fine solids are transported through the furnace at the velocity exceeding the terminal velocity of average particles, yet there is a degree of refluxing of solids adequate to ensure uniformity of temperature in the furnace. (Basu & Fraser, 1991, pp. 4)

CFB can be applied especially to the multi-fuel combustion and to the combustion of low quality fuels. (Kilpinen, 1995, pp. 257) In Figure 3 is shown a typical construction of a CFB boiler.

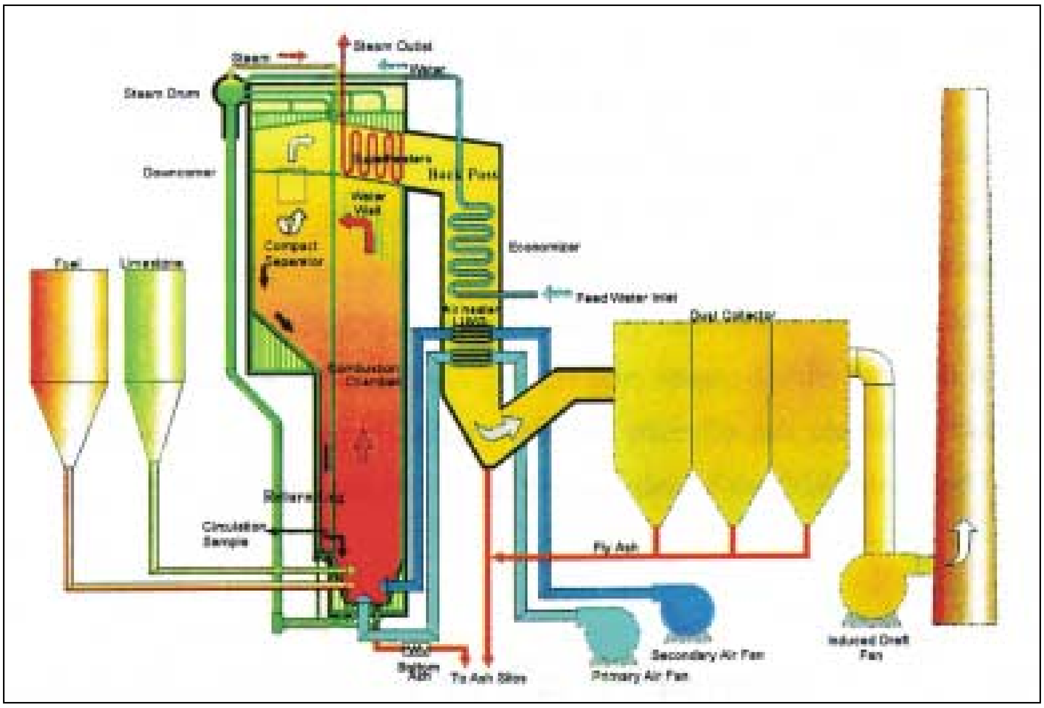


Figure 3. Circulating fluidized bed boiler (Foster Wheeler Energia Oy)

Fluidized bed boiler produces low NO_x emissions even without add-on pollution control equipment. NO, NO_2 and N_2O are emitted in significant quantities. Thermal NO is a minor contributor in the fluidized bed combustion, because the combustion temperature rarely exceeds 900 °C. Air feed is divided at least to the primary air and to the secondary air. Secondary air can be distributed to one or more delivery head lifts. This so-called staged combustion reduces NO emissions because it increases the amount of reducing char in the furnace. (Kilpinen, 1995, pp. 257)

2.1.2.1 NO Reactions

The formation of NO is a result of several homogeneous gas phase reactions and heterogeneous reactions. It is suggested that the most important NO reactions are homogeneous reaction with ammonia NH_3 (1) or heterogeneous oxidation with calcium oxide (2) and oxidation of char-nitrogen (3). (Kilpinen, 1995, pp. 264)

$$NH_3 \xrightarrow{+OH,+O} NH_i \xrightarrow{+O_2,+OH,+O} NO \qquad (1)$$

$$NH_3 \xrightarrow{+CaO,O_2} NO_x \qquad (2)$$

$$\begin{aligned} &O_2 + (-CN) + (-C) \rightarrow (-CNO) + (-CO) \\ &(-CNO) \rightarrow NO + (-C) \end{aligned} \qquad (3)$$

During devolatilization, fuel nitrogen is divided into char-nitrogen and volatile nitrogen compounds, mainly in the tar as NH_3 and HCN. During the combustion, the char nitrogen is oxidized to NO and N_2O, and also in some extent as NH_3 and HCN. In Figure 4 is shown a simplified reaction scheme for the formation and reduction of NO and N_2O.

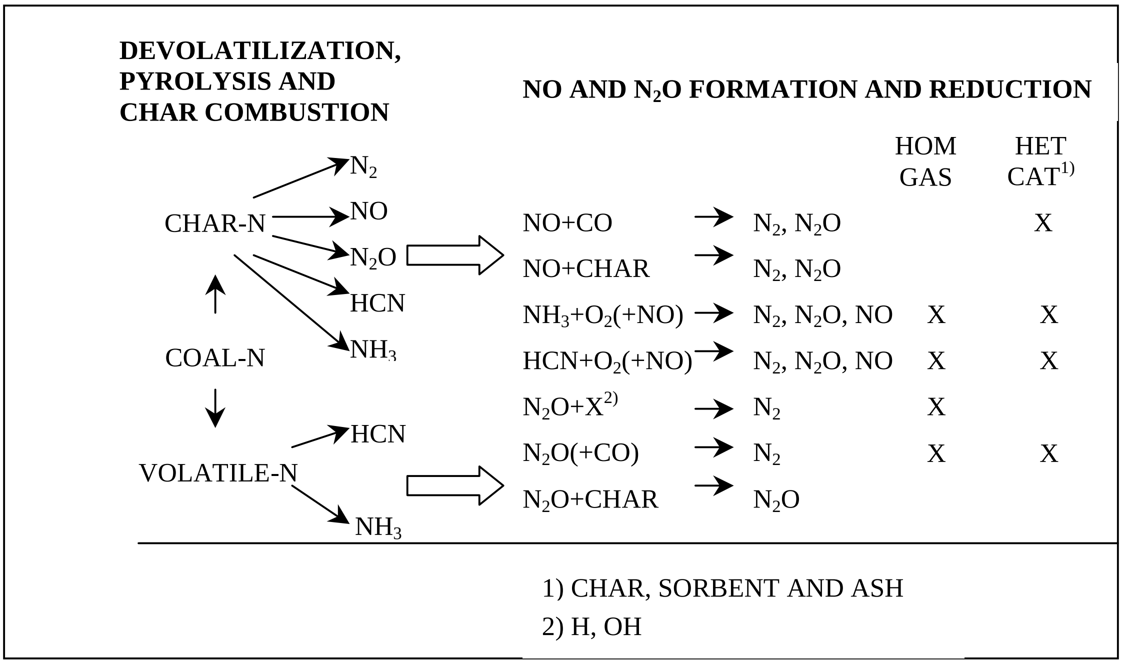


Figure 4. Simplified reaction scheme for the formation and reduction of NO and N_2O (modified from Johnsson, 1994, pp. 1398)

Division of the fuel-nitrogen between char and volatiles is very important for the emission formation, because the secondary reactions are quite different for the char-N and for the volatile-N. (Johnsson, 1994, pp. 1398)

2.1.2.2 N_2O Reactions

10-50 % of the volatile cyano- and cyanide compounds such as HCN will oxidize to N_2O in the temperatures of the fluidized bed combustion. The most important reaction is the following reaction (4):

$$\begin{aligned} HCN + O &\rightarrow NCO + H \\ NCO + NO &\rightarrow N_2O + CO \end{aligned} \quad . \tag{4}$$

Combustion temperature is a significant factor in the N_2O conversion. N_2O conversion stops when the combustion temperature exceeds 950°C, and it decreases while the combustion temperature increases. Thus, the N_2O conversion behaves quite the opposite compared to NO conversion. Therefore, it is always a question of optimization when the NO_x emissions of the CFB must be reduced. (Kilpinen, 1995, pp. 259)

2.1.2.3 Modeling of NO_x Emissions

As the understanding of combustion chemistry has increased, it has become possible to build detailed kinetic models of the nitrogen and hydrocarbon combustion kinetics. Concerning NO_x formation and destruction, comprehensive kinetic reaction schemes with several hundreds of reversible elementary steps have been developed. It is possible to examine the combustion kinetics of nitrogen oxides at wide temperature and stoichiometric ranges under atmospheric or lower pressure by comparing the predictions to careful measurements of radical and main species concentrations in flames. When these mechanisms are combined with simple flow assumptions like ideal reactors, many practical combustion problems can be analyzed. (Kilpinen & Hupa, 1998, pp. 330)

In Åbo Akademi in Turku, Finland, the detailed kinetic modeling of NO_x emissions in a circulating fluidized bed boiler has been studied. As the base of the model are elementary reaction mechanisms and the reactor concept. It is estimated that nitrogen chemistry at combustion includes at least 300 reactions involving 50 different species. There is a huge amount of reactions for three different types of NO_x formation. Simple reactor concepts used in modeling are perfectly stirred reactor (PSR) and plug flow reactor (PFR). Input values of detailed kinetic modeling are:

- Reaction system
- Kinetic constants $k_{+i} = A_i \cdot T^{\beta_i} \cdot e^{(-E_{a,i}/(RT))}$
- Thermodynamic constants $k_{-i} = k_{+i} / K_{c,i}$
- Reactor concept (PFR, CSTR)
- Concentrations at the inlet
- Temperature (T) and pressure (p).

Output values are the concentrations of the flue gas components as a function of residence time. (Kilpinen & Glarborg, 2000) A 1,5 dimensional model has been developed especially for CFB combustion. In the model, the furnace is divided into three zones. In Figure 5 is shown the general model structure and the calculation cells and flows of a 1,5-dimensional CFBC model.

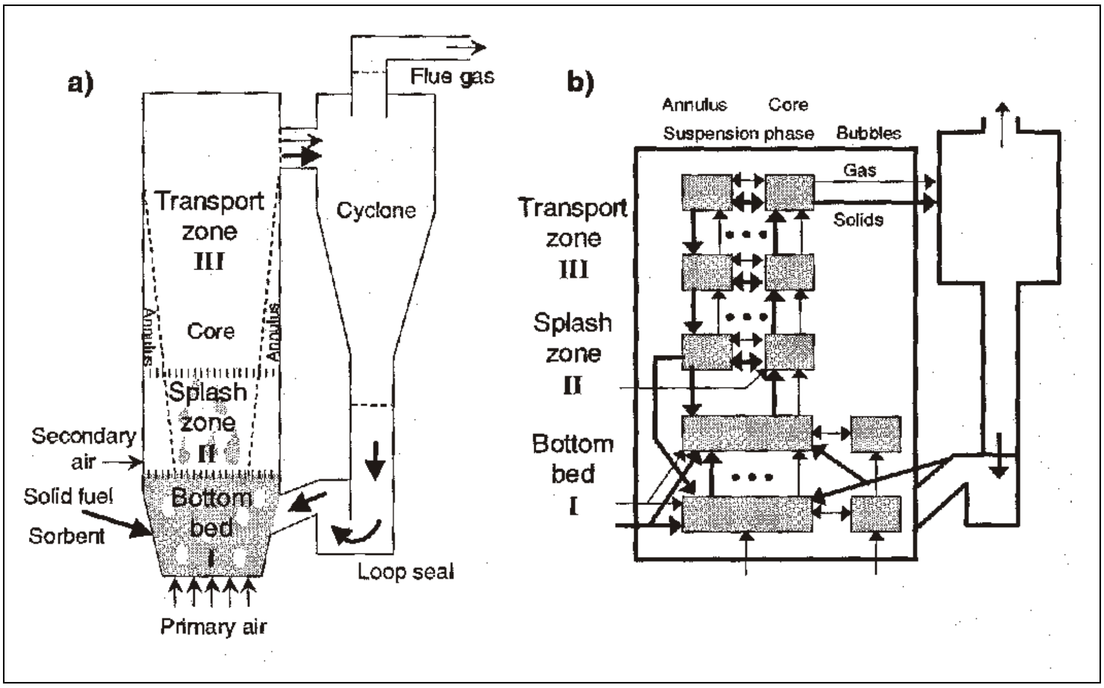


Figure 5. General model structure and calculation cells and flows of 1,5-dimensional CFBC model (Kilpinen et al., 2000)

The aim of the detailed kinetic modeling of CFBC is to create a general mathematical tool for studying the emission formation in a CFBC. The special interest will lie on ranking the different fuels and fuel mixtures according to their tendency to form nitrogen oxides. In Figure 6 is shown the principle of the NO_x emission tendency prediction.

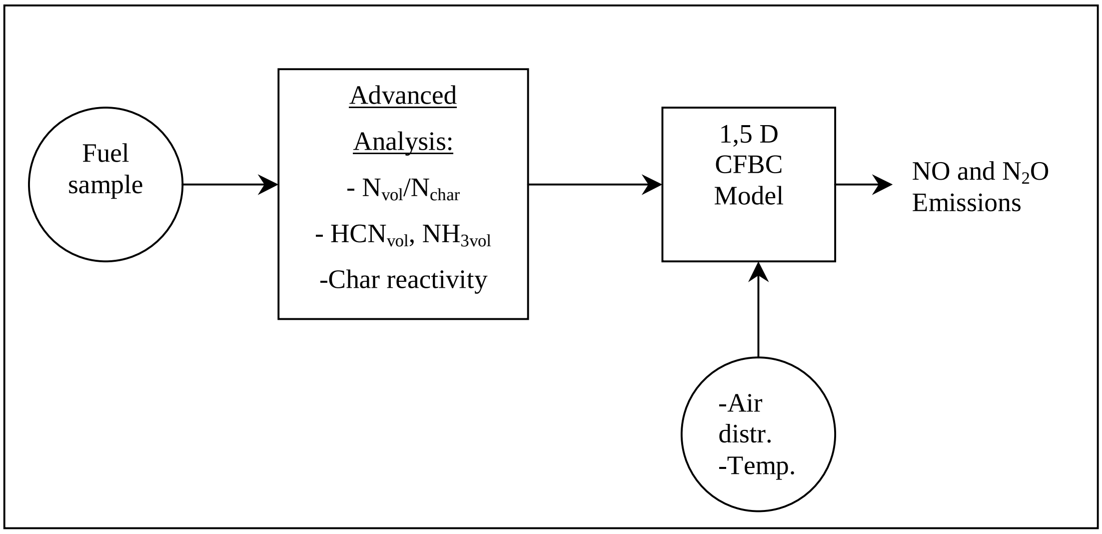


Figure 6. *NO_x emission tendency prediction (modified from Kilpinen et al., 2000)*

2.2 Measuring of Nitrogen Oxides

When emission gases must be measured, it should be carefully considered which methods are appropriate to the measurement place and to the measuring problem. A few options are available and choosing the right option is not easy. Measuring frequency, measuring accuracy and the financing of the measurement should be considered in advance. There are different ways to organize the chosen method. Measuring can be divided into the analyzing and into the periodic and continuos sampling. (Niskanen, 1985, pp. 9) Measurement can be done as in situ –measurement directly at the sampling place or sample can be led to the analyzer via sampling line. The latter method is called extractive or diluting sampling. (Torvela, 1993, pp. 24-25)

Nitrogen oxides are usually measured continuously at the power plants. Periodic measurements can be done for example during the commissioning of the power plant or during the tests of the continuous measuring equipment. Some periodic measurements are statutory. In the continuous measuring, the sample is collected with a diluting sample unit and led to the analyzer. It may be also necessary to convert other nitrogen oxides to NO in a catalytic converter

2.2.1 Diluting Sampler

Detection limits of the NO analyzers are in the range of few ppb (parts per billion by volume), although original emissions in the flue gases are somewhat hundreds of ppm (parts per million by volume). Because of this, the sampling must be done with a diluting sampler unit. Sample is diluted with dry instrument air to prevent condensing in the sampling line. (Torvinen, 1993, pp. 85) The diluting ratio, presented in Equation (5), is typically between 1:2 – 1:150.

$$\textit{Diluting ratio} = \frac{Q_2}{Q_1 + Q_2} \tag{5}$$

The principle of diluting stack probe is presented in Figure 7.

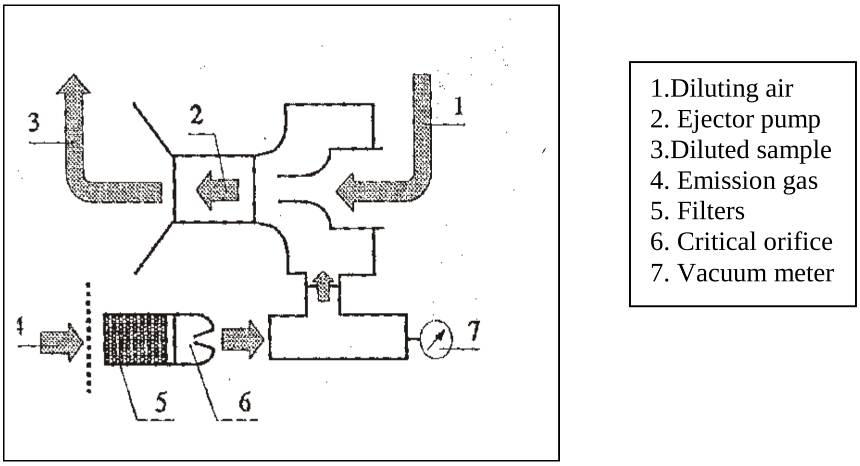


Figure 7. Principle of the diluting stack probe. (modified from Torvinen, 1993, pp. 104)

In diluting, the gas sample is collected through a critical orifice mounted inside the stack probe. Gas sample will be sucked from the stack through the filter with help of the ejector pump. Diluting air creates a partial vacuum in the probe. The diluting air is heated with the heat exchanger integrated into the probe to prevent the effect of temperature difference to the diluting ratio. In diluting, the moisture amount decreases in relation to the diluting ratio. (Niskanen, 1985, pp. 40-41)

2.2.2 Analyzing Methods of Nitrogen Oxides

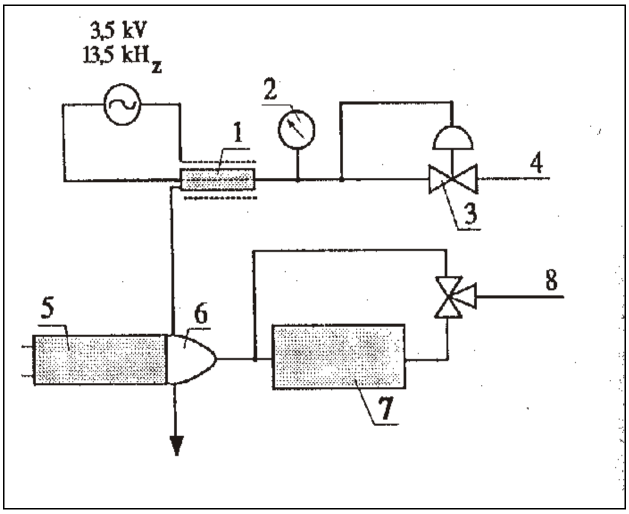
The most commonly used method for the measurement of nitrogen oxides is based on chemiluminescence. In chemiluminescence, a light quantum is generated as a result of a chemical reaction. Other methods are based on UV-VIS/IR –spectroscopy. These methods are suitable for continuous sampling-based measuring. (Niskanen, 1985, pp. 126)

2.2.2.1 Chemiluminescence

In some chemical reactions, the reaction products remain in excited state and radiate light, when the reaction is discharged. This phenomenon is called chemiluminescence. Excitation is discharged as a radiation particularly at low pressures, where collision frequency is low. The following reactions describe the interaction between NO and ozone:

$$\begin{aligned} NO + O_3 &\rightarrow NO_2^* + O_2 \\ NO_2^* &\rightarrow NO_2 + h\nu. \end{aligned} \tag{6}$$

The ozone needed for the reaction is produced from pressurized air or pure oxygen in an ozone generator. A photo-multiplier tube measures the intensity of the chemiluminescence through an optical filter and converts it to a current signal. In Figure 8 is presented an instrument based on chemiluminescence for the measurement of nitrogen oxides.



1. Ozone generator
2. Manometer
3. Oxygen controller
4. Air
5. Photomultiplier tube
6. Reaction chamber
7. NO_x converter
8. Gas sample

Figure 8. *An instrument for the measurement of nitrogen oxides based on chemiluminescence. (Torvinen, 1993, pp. 86)*

This system generates a broadband light with a wavelength between 500 and 3000 nm and with a maximal intensity at 1100 nm. Chemiluminescence method is very sensitive and its detection range is only a few ppb by volume. It measures only the NO-concentration, but it can be used for measuring NO_2 as well. Usually, NO_2 is converted to NO in a catalytic converter. The sample is often divided into two streams, one of which is led directly to the measurement chamber, and the other runs through the converter. The difference between these two measurements gives the concentration of NO_2. (Torvinen, 1993, pp. 85-87)

2.2.2.2 Other Methods for Measuring NO_x

Other methods are based on the absorption of light in the gas molecules. Such NO_x measuring methods are NDUV, NDIR, FTIR and DOAS. NDUV analyzer operates at the visible UV–area and NDIR at the IR-area of 2-12 µm. Both of the analyzers can be used to detect NO and NO_x. In their combination, NO is measured with IR-absorption, and NO_x synchronous with UV-absorption. The light emitted from the IR- and UV-sources is divided into two different rays, one of which goes through the measuring chamber and the other through the reference chamber. In the measuring chamber, the gas sample absorbs radiation, and in the reference chamber it doesn't. The intensity difference between these two rays indicates the concentration of measured gas. (Hernberg & Linna, 1995, pp. 555-556)

FTIR-analyzer operates in the area of the whole infrared spectra. It is capable for analyzing several gases at the same time and the disturbing compounds can be recognized from the spectrum. Most molecules, particularly the small ones, have such specific features at the infrared spectra, which enable them to be identified. Small molecules can be separated with the high resolution instruments and their concentrations can be determined. When measuring N_2O, FTIR is the only reliable continuous method. In the operation of a dispersive infrared spectrometer, which utilizes Fourier transformation, two light beams pass through the different paths and interfere. The interferogram is obtained by a detector, and processed with a computer. Beams are separated with a semitransparent mirror, or a beam splitter. One beam is reflected from a fixed mirror and the other is reflected from a moving mirror, by means of which the interference is formed. This technique is based on the Michelson interferometer. (Torvinen, 1993, pp. 120-123)

2.3 Nitrogen Oxides Abatement

When selecting the right nitrogen oxides control strategy, the degree of emission reduction needed, the type of fuel, the combustion device design and the operational factors must be considered. Before selecting the control technology, it is necessary to understand how the NO_x emission is formed. NO_x emissions formed during the combustion processes are a function of the fuel composition, the combustion equipment and the operating mode and basic design of the boiler. It should be taken into account that the efficiencies of the NO_x control technologies are not additive, but rather multiplicative. It is not worth combining technologies with the same principle, since it would not provide further NO_x reduction than either of the combination. All of the available control technologies have the potential for affecting the performance and the operation of the unit. Such potential impacts should be carefully evaluated before selecting the applicable control technology. (Wood, 1994, pp. 32-38)

One way to meet the new constraint, taxes and political expectations has been to switch the fuel (see Table 1.), while in the last decade, the NO_x charge in Sweden has made it economic to reduce the NO_x emissions of all kinds of fuels. There has been a question whether to clean the flue gases, or to modify the combustion systems. In general, combustion modifications have been much cheaper, although less effective. The investment costs of the NO_x abatement have decreased, when the competition between manufacturers has increased. That illustrates how dynamic the operation field is, when choosing the right reduction method for nitrogen oxides. (Strömberg & Åbyhammar, 1999, pp. 37)

In fluidized bed combustion, the circumstances are optimal for reducing nitrogen oxides. Low combustion temperatures, air staging and particularly long retention times of gases and non-combustibles in the fluidized bed boiler increase the reduction of nitrogen oxides. (Jaanu, 1987, pp. 55) In the Figure 9 are presented the FBC parameters, which affect the NO_x emission.

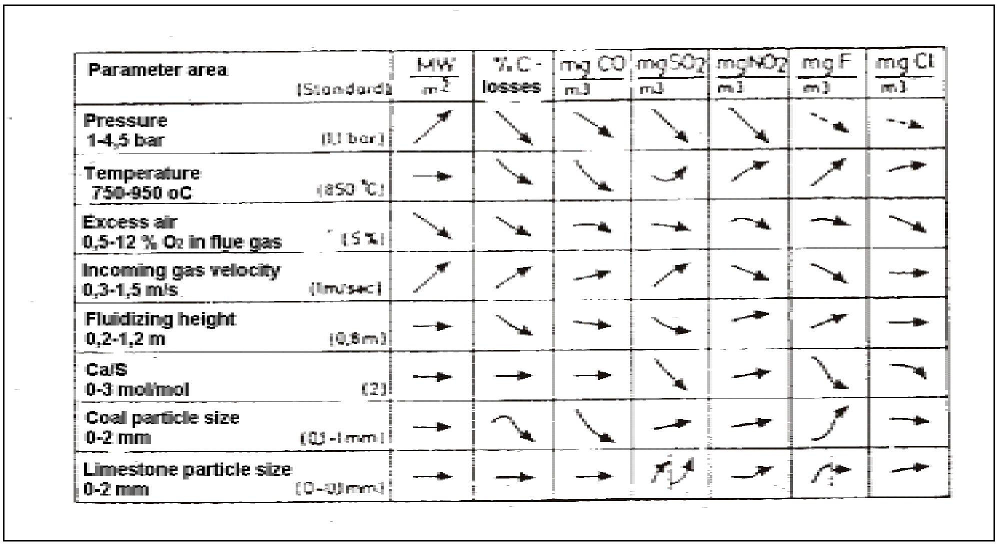


Figure 9. FBC parameters and their effect on NO_x emissions (Jaanu, 1987, pp. 56)

To prevent the fuel-N leaving the furnace as NO_x, the combustion gases should be maintained fuel-rich long enough for the N_2 forming reactions to proceed. Since the conversion of fuel-N to NO is only weakly dependent on temperature, the methods, which are effective for thermal NO have only little influence on fuel NO. (Flagan, 1988, pp.191)

2.3.1 Combustion Modifications

Following measures are included in the group of combustion modifications:

- burner optimization: excess air control, burner fine tuning
- air staging: overfire air or two-staged combustion
- flue gas recirculation
- fuel staging: burner out of service, fuel biasing, reburning or three-stage combustion
- low NO_x burners. (Soud & Fukasawa) 1996, pp. 32)

Air staging and flue gas recirculation can be applied also in a circulating fluidized bed boiler. They affect mainly the conversion of volatile nitrogen compounds to NO_x. (Hiltunen, 1990, pp. 206-209)

2.3.1.1. Air Staging

In CFB boilers, air supply is divided into the primary and secondary air. Primary air is introduced through the air distribution grid. The location of secondary air has significant impact on the NO_x emissions. Secondary air can be introduced to the one or more boiler levels. In Figure 10 is presented the effect of the secondary air location on the NO_x emissions.

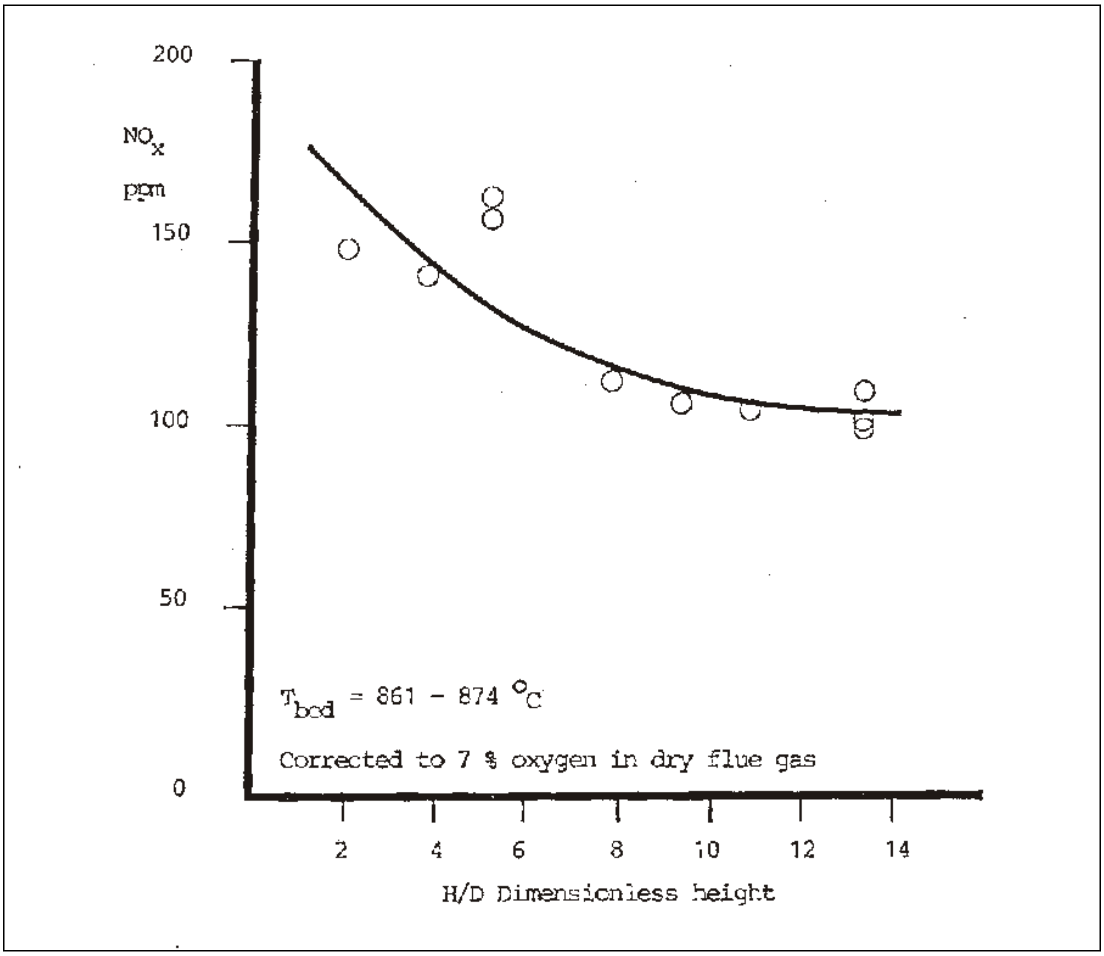


Figure 10. NO_x emissions as function of relative height location of the secondary air nozzles when burning brown coal. (Hiltunen & Tang, 1988, pp.432)

In the placement of the secondary air, the aim is to reach a balance between a good NO_x reduction and high combustion efficiency. The optimal secondary air location must be especially designed for each fuel type. The staged combustion creates a fuel-rich environment to the lower part of the boiler, and the nitrogen oxides will be reduced by char and CO. Secondary air injection ensures good carbon, CO and hydrocarbon burnout. Air staging is effective particularly for medium-to-high volatile fuels such as biomass. The application of staged air prevents organically bound nitrogen in the volatile matter from oxidizing and forming NO_x. (Hiltunen & Tang, 1988, pp. 430-432) About 30 % NO_x reduction can be achieved with air staging. (Hiltunen, 1990, pp. 208)

2.3.1.2 Flue Gas Recirculation

In multifuel-fired fluidized bed boilers, flue gas recirculation (FGR) is applied to control the temperature in the lower part of the boiler. Another function of FGR is to control the heat exchange of the superheaters. (Ekono Oy, 1989, pp. 47) By recycling 20-25 % of the flue gas back to the furnace through the grid, NO_x emissions can be reduced about 50 %. The NO_x reducing effect of the flue gas recirculation is based on the decrease in the combustion temperature and in the availability of oxygen. With low grade fuels, flue gas recirculation cannot be used because the low heating value of the fuel. (Hiltunen, 1990, pp. 208) Flue gas contains mainly CO_2, N_2 and H_2O. Flue gas is cold and inert gas, which inhibits NO_x formation reactions in the furnace of the fluidized bed boiler.

2.3.2 Selective Non Catalytic Reduction SNCR

Selective non-catalytic reduction (SNCR) of nitrogen oxides means that a reagent such as ammonia (NH_3) or urea, is injected into the flue gas within appropriate temperature window to reduce NO_x emissions 30-50 % without a catalyst. The main reactions are:

$$NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (with\,ammonia) \quad (7)$$

$$\begin{aligned} &NO + 2CO(NH_2)_2 + O_2 \\ &\rightarrow 4N_2 + 2CO_2 + 4H_2O \quad (with\,urea). \end{aligned} \quad (8)$$

A typical SNCR system consists of the reagent storage, multi-level reagent injection equipment and associated control instrumentation. In Figure 11 is presented a typical arrangement of the SNCR equipment.

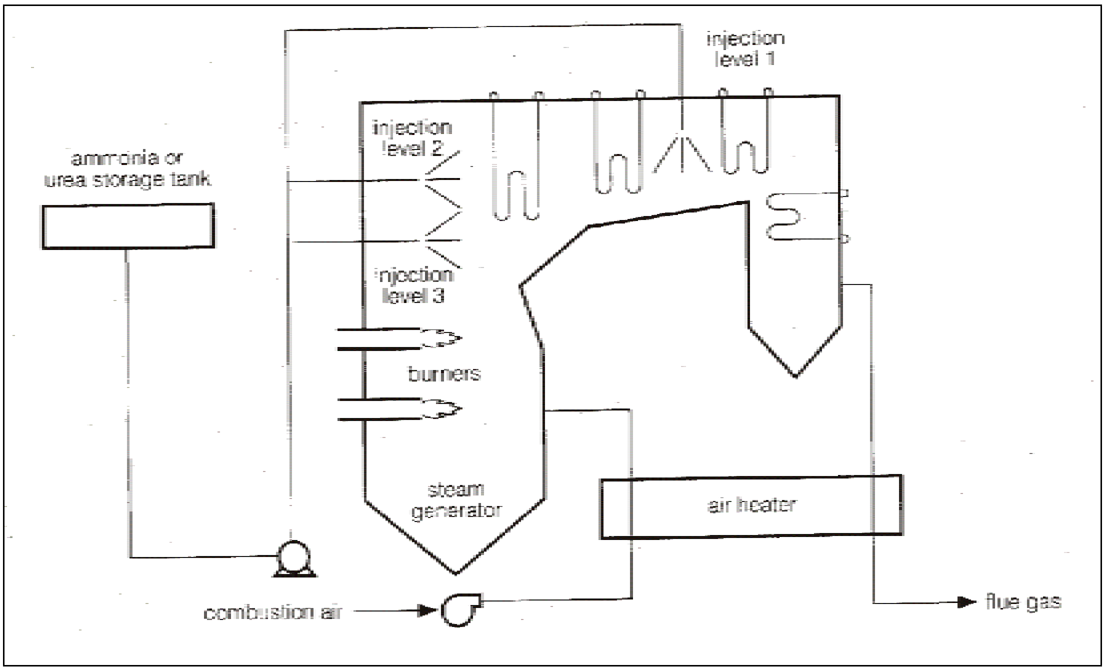


Figure 11. Typical arrangement of the SNCR equipment (Soud & Fukasawa, 1996, pp. 73)

The efficiency of the SNCR process depends, in addition to appropriate temperature of the gas, on the reagent mixing with the gas, the residence time within the temperature window and the amount of reagent injected relative to the concentration of NO_x present. (Wood, 1994, pp. 37) The narrow temperature window is located between 850-1100°C and it is centered at about 975°C. In a CFB boiler, a common bed temperature is 850°C, which is just at the lower limit of the temperature window of the process for relevant residence times. At low boiler loads, the temperature usually drops below the lower temperature limit. Good results have been obtained in CFB boilers in spite of the temperatures as low as 800°C, but then the ammonia slip and CO emission increase. (Leckner et al., 1991, pp. 2396) When temperature rises above 1100°C unwanted NO may be formed. In Figure 12 are presented reactions in different temperatures, when the reagent is ammonia.

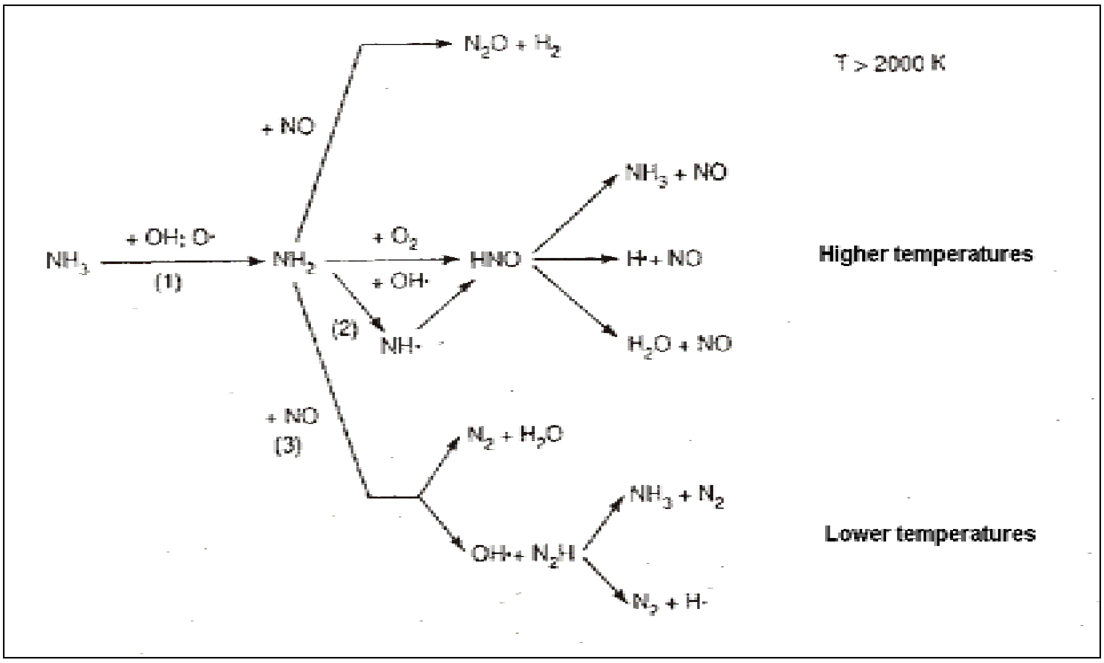


Figure 12. Ammonia reactions in different temperatures. (Förstner, 1992, pp. 404)

The increase of the ammonia slip has some negative effects such as corrosion of the following heating surfaces and the fouling of the air pre-heater. The ammonia concentration in the fly ash and in the reaction products of the possible desulphurization must be kept as low as possible so that they can be reused. (Förstner, 1992, pp. 405)

The reagent utilization can be measured as the amount of reagent to remove a given amount of NO_x. The molar ratio is defined as the number of ammonia moles required to remove one mole of NO_x. (Soud & Fukasawa, 1996, pp. 73-74) At the temperatures of the fluidized bed combustion, and with a typical emission level of 150 ppm, 50 % NO_x reduction is achieved with molar ratio of 1 - 2. The molar ratio needed for similar reduction as before increases when the NO_x level or gas temperature decreases. (Hiltunen, 1990, pp. 208-209) In Figure 13 is illustrated the molar ratio of ammonia use in selective non-catalytic reduction.

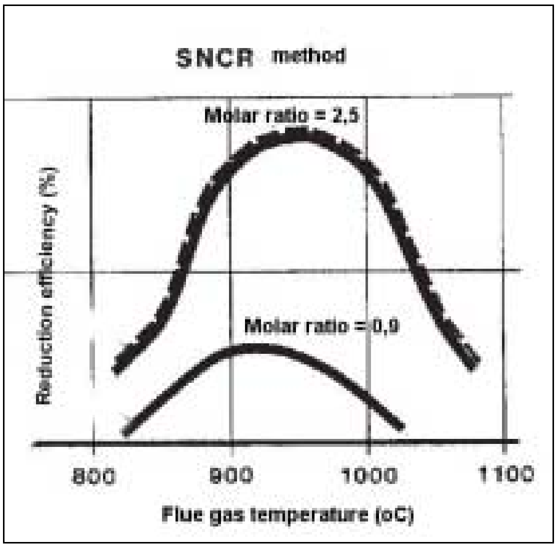


Figure 13. Ammonia use in selective non-catalytic reduction. (Ekono Oy, 1989, pp. 52)

Control of the ammonia injection is difficult since there is no opportunity for effective feedback. A continuous, real-time ammonia slip measurement improves the control of the ammonia injection. The ammonia injection system must be able to feed the reagent where it is most effective within the boiler because NO_x distribution varies within the cross section. Multiple layers of ammonia injection as well as individual injection zones in cross-section of each injection level are commonly used to follow the temperature changes caused by the boiler load changes. (Soud & Fukasawa, 1996 pp. 72)

2.3.3 Selective Catalytic Reduction SCR

The most effective method for NO_x abatement at the moment is selective catalytic reduction (SCR). In the selective catalytic reduction, the NO_x concentration of the flue gas is reduced with the ammonia injection in the presence of the catalyst. In the temperatures between 300-400°C, 90 % reduction can be reached because of the following catalytic reactions: (Ahonen, 1996, pp. 96-97), (Soud & Fukasawa, 1996, pp. 62)

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (9)$$

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O \quad (10)$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad (11)$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (12)$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O\,. \quad (13)$$

Heterogeneous catalytic reaction can be divided into five phases:

1. Transportation of the reactive components to the catalyst surface assisted by the diffusion and the flow
2. Adsorption to the catalyst surface
3. Surface reaction
4. Desorption of the reaction products from the catalyst surface
5. Transportation of the reaction products from the catalyst surface assisted by the diffusion and the flow (A. Ahlström, 1987, pp. 6)

A typical SCR system has following parts: reagent storage, delivery equipment, vaporization and injection system for the reagent, SCR reactor, catalyst, soot blowers and additional instrumentation. Anhydrous or aqueous ammonia are commonly used as the reagents. (EPA, 1997, pp. 3) In Figure 14 is presented a typical construction of the SCR reactor.

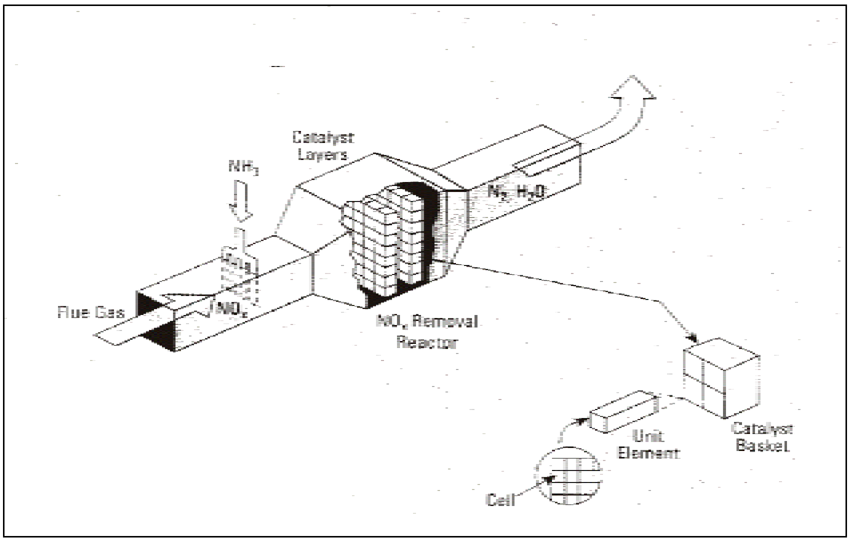


Figure 14. Typical construction of SCR reactor (Cho, 1994, pp. 40)

The catalyst can be placed at different locations in the flue gas flow. The most important parameter when considering location is the flue gas temperature. There are three main options to place the catalyst. They are called high dust, low dust and tail end locations. These three locations are presented in Figure 15.

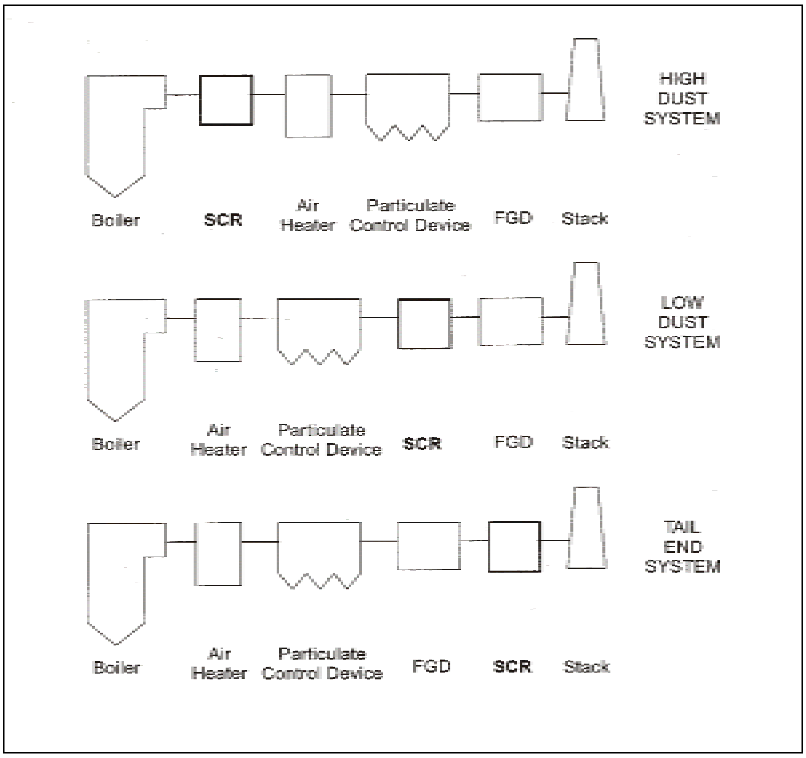


Figure 15. SCR configurations (EPA, 1997, pp. 4)

In the high dust application, the flue gas contains all the dust and sulfur oxides from the combustion. In the low dust application, the flue gas still contains sulfur oxides but no longer dust. In the tail end application, the flue gas contains no more dust and sulfur oxides, but the temperature for the NO_x abatement is too low, and reheating is required. Sulfur and fouling by the dust can cause deactivation of the catalyst. The main reasons for the catalyst deactivation are as follows:

1. Chemical deactivation by a poisoning substance: sulfur, arsenic, alkali, alkaline earth metals.
2. Thermal deactivation by sintering, loss of surface area or support collapse
3. Mechanical deactivation by fouling (Ahonen, 1996, pp. 97-99)

The catalysts have a shape of either plates or honeycombs. Plate catalysts have a metal net around the catalyst material. They can be placed in temperatures between 300-450°C. In the honeycomb catalysts, the catalyst material is extruded to the square or honeycomb form. The suitable temperature window for them lays between 150-550°C. Plate and honeycomb catalysts are so called metal oxide catalysts. The most common support material for the catalysts is titanium oxide (TiO_2). The most common active components are V_2O_5, WO_3 and MoO_3. (Bárzaga-Castellanos et al., 1998, pp. 313-314) Different configurations of the catalysts are shown in Figure 16.

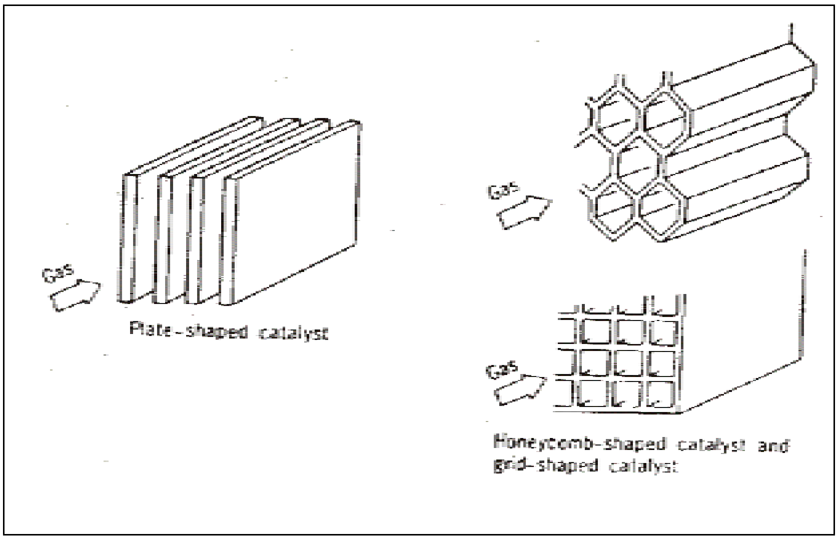


Figure 16. Configurations of the parallel flow catalysts (Ahonen, 1996, pp. 107)

The molar ratio of the ammonia fed is 1,0, which keeps the ammonia slip low. In Figure 17 is presented the molar ratio of the ammonia use in SCR method.

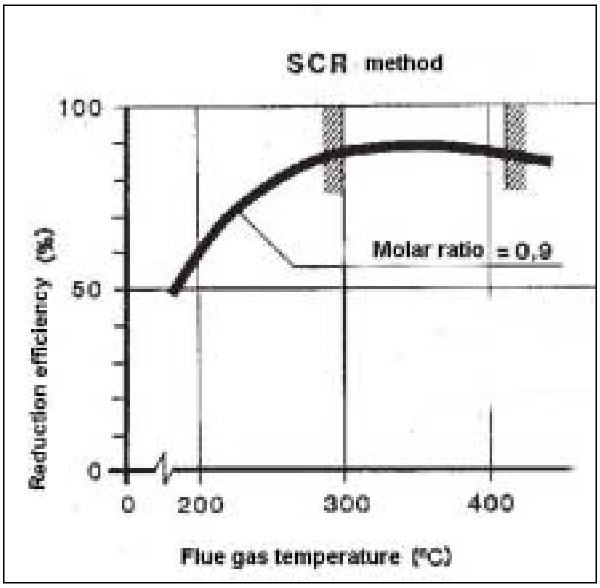


Figure 17. Ammonia use in the selective catalytic reduction. (Ekono Oy, 1989, pp. 52)

Ammonia slip should be kept under 5 ppm. Increase of the ammonia slip reveals that catalyst is deactivating, and it should be replaced, or an additional catalyst should be installed. Limiting ammonia slip under 2 ppm permits the utilization of the fly ash, and prevents the fouling of the downstream equipment. (Soud & Fukasawa, 1996, pp.64) The effect of catalyst performance degrades in the course of time because of fouling, poisoning and degradation of the catalyst material. The catalyst performance should be observed by taking samples from the catalyst and by measuring its performance. (Bárzaga-Castellanos et al. 1998, pp. 314) In Figure 18 is shown the time dependence of the catalytic activity.

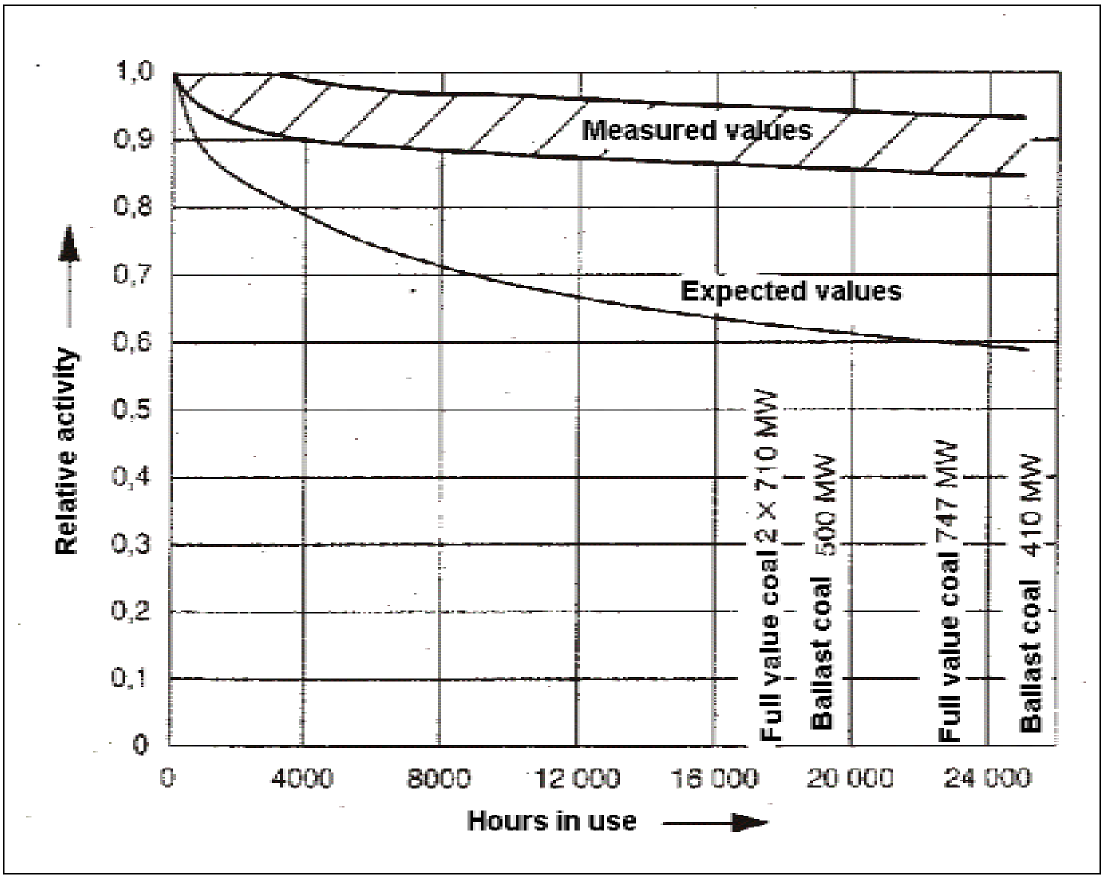


Figure 18. Time dependence of the catalytic activity (Farwick et al. 1993, pp. 438)

There have been some attempts to regenerate the catalysts. The aim of the catalyst regeneration is to extend its lifetime and to improve the economic and technical possibilities to use an SCR in the combustion of the biomass. Such regeneration methods are for example a wash with the water or a treatment with the sulfur oxide. In fluidized bed combustion, the main contributor of the catalyst deactivation is short residence time between final combustion and catalyst as the large part of the combustion takes place in the freeboard of cyclone. Sulphatisation with SO_2 has been successfully applied in the laboratory conditions. About 80 % of the lost activity was regained by using the sulphatisation. The recommendation is to sulphatize with 500 ppm SO_2 during at least 16 hours at as high flue gas temperature as possible. The water wash will remove the potassium on the catalyst, which brings the additional 6 % higher activity than sulphatisation alone. (Andersson et al., 2000)

2.3.4 Hybrid SNCR/SCR

A hybrid system is defined as follows:

A hybrid system is a system that combines SNCR injection of a reagent into the boiler with an SCR catalyst, which utilizes the ammonia slip for further NO_x reduction.

First hybrid systems were installed to oil-fired boilers in Japan in the early 70's. Hybrid system (see Figure 19.) is an attempt to combine the low capital cost of an SNCR system with the high reduction rate and low ammonia slip of an SCR system. (Soud & Fukasawa, 1996, pp. 80)

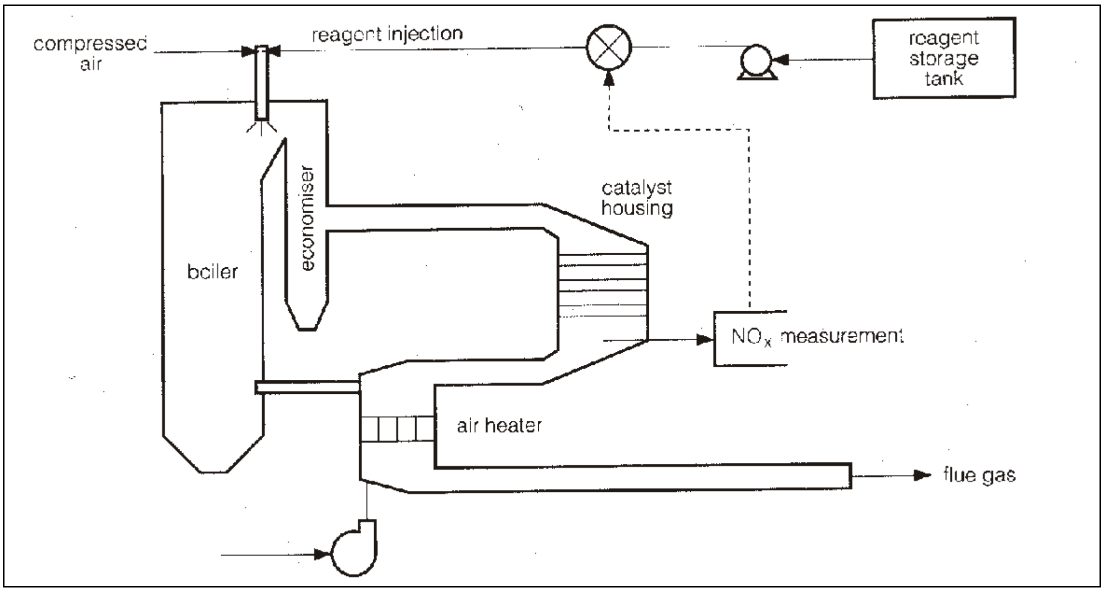


Figure 19. Hybrid SNCR/SCR system (Soud & Fukasawa, 1996, pp. 81)

A hybrid system is expected to be more flexible for a load change than an SNCR or an SCR. By adding a catalyst after the SNCR system, the NO_x reduction rate can be increased 10-12 % because of the higher ammonia slip allowed. With the lower load, temperature decreases in injection points and the ammonia slip increases. Then NO_x reduction occurs mainly in the catalyst. If the ammonia distribution is inadequate, no further NO_x reduction occurs in the catalyst. The same applies conversely, letting ammonia pass catalyst unreacted when the NO_x concentration is adequate. Control of the ammonia distribution is a challenging task with varying NO_x concentrations. (Niemann et al., 2000, pp. 4), (Soud & Fukasawa, 1996, pp. 80)

With a hybrid system, it is technically feasible to reach the NO_x reduction up to 90 % with ammonia slip less than 5 ppm. The cost advantages compared to full scale SCR system can be reached only if the catalyst volume of the hybrid system is smaller than the catalyst volume of the SCR system. A hybrid system always requires more reagent than a full SCR system. Cochran et al. have estimated that the break-even point for the use of the hybrid system is at the NH_3/NO_x distribution ratio of 30 % when total NO_x reduction required is 70 % and ammonia slip allowed is 5 ppm (see Figure 19). Then the catalyst volume of the hybrid system reaches the catalyst volume of the full scale SCR, and use of the hybrid system is no longer profitable. (Soud & Fukasawa, 1996, pp.80-81)

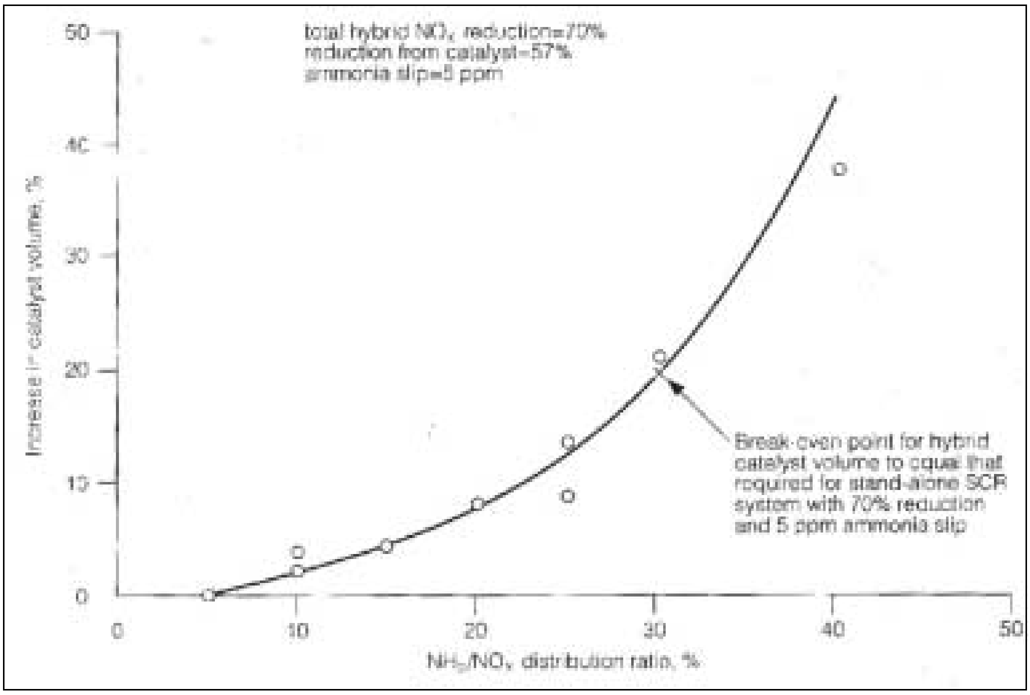


Figure 20. Effect of the NH_3/NO_x distribution ratio on increase in catalyst volume. (Soud & Fukasawa, 1996, pp.81)

2.3.5 Other Methods for NO_x Abatement

There are also several other options to reduce the NO_x emission, but they aren’t yet fully developed for commercial use. The catalytic reduction of the NO_x, non-selective oxidation of the NO_x and combined techiques for SO_x/NO_x removal can be mentioned as the examples from the other methods. (Vidqvist, 1993, pp. 21)

Use of a catalytic bed material has been studied in the fluidized bed combustion. The mixture of solids in the FBC usually consists of char, sand, ash and possibly also limestone. In general, char and calcined limestone have a high catalytic activity, but the activity of the limestone decreases in the course of sulfation. The activity of quartz sand in the presence of CO may be a potential option for the NO_x –reduction in the furnace. It has been found that the activity of the quartz sand is related to the content of the impurity Fe_2O_3. (Johnsson, 1994, pp. 1406-1409)

The lime or limestone-based desulphurization system is in general a wet process, while SCR is a dry process. This allows each desired removal efficiency to be set independently of the inlet SO_x/NO_x concentration ratio. Typical dry processes for the combined removal are:

1. Solid adsorption/regeneration
2. Gas/solid catalytic processes
3. Irradiation
4. Alkali dry spray.

Typical wet processes for the combined removal are:

1. Oxidation/absorption
2. Iron chelates.

(Soud & Fukasawa, 1996, pp. 82)

3. PROCESS CONTROL METHODS FOR FLUIDIZED BED COMBUSTION

Boiler control is a broad subject that includes the total start up and shutdown procedures, as well as safety interlocks and the on-line operation of the boiler. A boiler control system is an interconnected package of control loops and functions into which a number of inputs are connected, and from which a number of output signals are delivered to final control devices. A change in one input will have an effect on more than one boiler measurement or output. There exists a goal in the improvement of the control system to minimize these interactions. (Dukelow, 1995 pp. 1-3) Emissions control is nowadays becoming more and more important also in fluidized bed combustion. Because the emissions are strongly dependent on process conditions, it is important to optimize and control process values so that the emissions are minimized. (Karppanen, 2000a, pp. 37)

3.1 Control Loops of Fluidized Bed Boiler

Similar control applications and methods can be applied both to bubbling fluidized bed boiler and to circulating fluidized bed boiler, although they have certain differences in combustion and in emissions formation. The aim of the CFB combustion control is to reach a better efficiency, and to reduce the emissions for example in the situations where the fuel quality or the boiler load are continuously changing. (Kinnunen, 2000, pp. 72)

Main control loops of the CFB boiler are as follows:

- Steam pressure control by changing the fuel feed rate
- Steam temperature control with water injection
- Flue gas O_2 content control
- Combustion air distribution control
- Drum level control
- Superheated steam pressure control

- Combustion chamber pressure control
- Bed pressure control.

(Karppanen, 2000a, pp. 55), (Huhtinen et al., 1995, pp. 244-245) The main control loops of the CFB boiler are presented in the following figure:

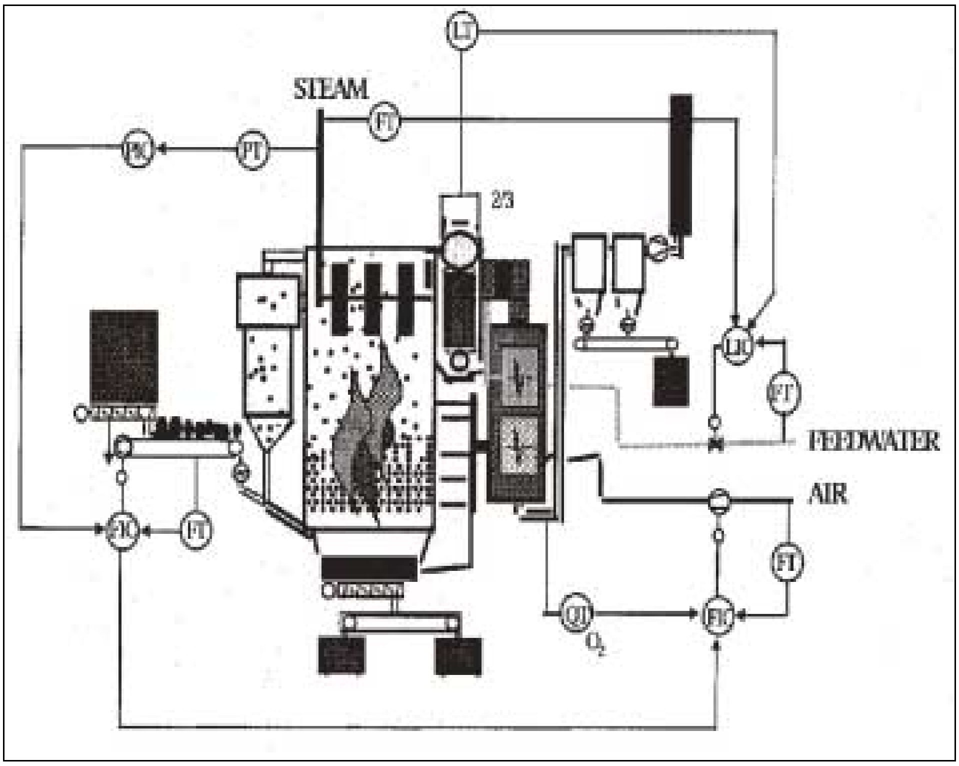


Figure 21. Main control loops of the CFB boiler (Karppanen, 2000, pp. 56)

Some of these main control loops have interaction with the NO_x emission. Such control loops are steam pressure control, combustion air distribution control and bed temperature control.

3.1.1 Steam Pressure and Temperature Control

Steam pressure deviation is an indication of boiler load deviation, and it is controlled with a change in the fuel feed rate. Pressure control is realized either as a boiler following control or as a turbine following control. In boiler following control, the control systems for the boiler and turbine are uncoupled and separate. If the load increases, the steam pressure begins to drop. This activates the combustion control system to increase the firing rate, and to bring the steam pressure back to its set point. In turbine following control, the pressure remains constant and changes in load are handled with changing the firing rate. This causes the rise in the throttle steam pressure and the turbine valves are opened by the turbine throttle backpressure control. A typical control solution is PID-type control, in which the steam pressure controller is regulated with a correction term from the steam flow. (Karppanen, 2000a, pp. 56), (Dukelow, 1991 pp. 123-133)

3.1.2 Combustion Air Distribution Control

Combustion air control ensures that the correct amount of air is distributed to the boiler related to the fuel feed rate. Fuel rich environment in the furnace is a potential risk for incomplete combustion and for CO emissions. Too big amount of excess air increases the nitrogen oxide emissions and the thermal losses of the flue gas. The most important factors in the combustion air control are fuel feed rate and O_2 content of the flue gas. O_2 content will be given to air ratio controller as feedback. The total air requirement is divided between primary, secondary and possible tertiary air. For each load case, there is an air distribution curve, according to which air amount for different load cases is determined. (Karppanen, 2000a, pp. 57-59)

3.1.3 Bed Temperature Control

Bed temperature must be maintained high enough to ensure the adequate combustion rate and low enough to avoid the sintering or the melting of the bed. Fuel quality, primary/secondary air distribution ratio, amount of primary air and degree of flue gas recirculation are the parameters which have an effect on the bed temperature. The temperature-lowering effect of wet or low-quality fuel can be compensated by using an auxiliary fuel (coal, oil or gas). (Karppanen, 2000a, pp.62) An indication of the bed temperature change may indicate an incorrect total amount of bed material or the incorrect amount of fuel in the bed relative to other materials. If the problem is an incorrect amount of the bed material, the solution is to drain material from or add material to the bed. If the problem is an incorrect amount of the fuel relative to the bed material, an alternative would be to trim the fuel input rate from the bed temperature. (Dukelow, 1991 pp. 392)

3.2 Traditional Control Methods

When planning the control concept, it is essential to know the system as well as possible. Especially, the physical properties of the system have a determinant position in the design of the control circuits. The physical properties determine the dynamic behavior of the system. The system description with the physical equations is called a model. A model is the basis of the control theory. A control system is described with the following definitions: the model, the initial state and the reactions of the system. (Schlitt, 1988 pp. 17) There are two main approaches to form a model: the first principle approach (white box) and identification of a parameterized black box –model. The first principle approach based on the physical laws and relationships is the basis of the traditional control. (Ikonen & Najim, 2001 pp. 3)

Control systems consist of different partial systems, which are called transfer elements or functional blocks. The whole system can be presented as a block diagram, which consists of partial systems and the signals between them. (Sinervo, 1997, pp. 1-2) The functional block is a symbol for the mathematical operation on the input signal to the block that produces the output. In Figure 22 is presented a basic control circuit.

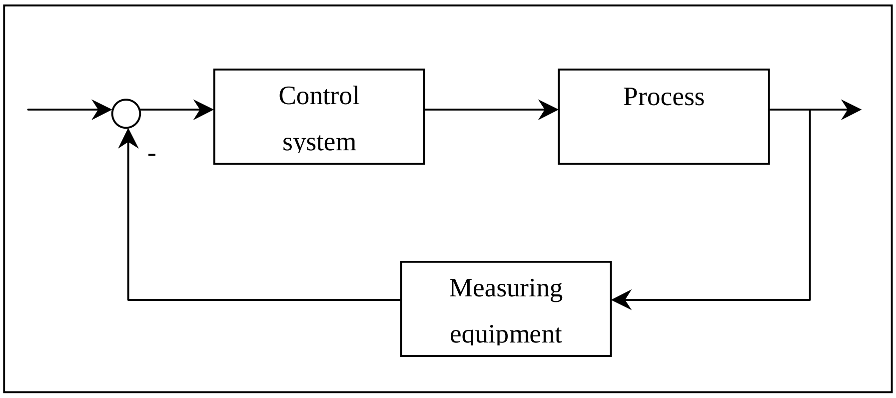


Figure 22. Basic control circuit (modified from Lautala, 2000, pp. 9)

The advantages of the block diagram representation lie in the fact that it is easy to form an overall block diagram for entire system by connecting the blocks of the components according to the signal flow, and that it is possible to evaluate the contribution of each component to the overall performance of the system. (Ogata, 1997, pp. 63-64)

When designing a control system, one must be able to predict the dynamic behavior of the system from the knowledge of the components. The most important characteristic of the dynamic behavior of the control system is the absolute stability, which means that the system is whether stable or unstable. The stability concept includes the rest position of the system, the oscillation process related to the process dynamics and the permanent oscillation. A linear time-invariant control system is stable if the output eventually comes back to its equilibrium state when the system is subjected to an initial condition. A linear time-invariant system is critically stable, if oscillations of the output continue forever. (Ogata, 1997 pp. 135) There are two basic methods to solve the stability of the control circuit: root locus diagram and Nyquist criterion together with Bode representation. (Schlitt, 1988 pp. 153)

3.2.1 Basic Control Functions

Improvement of the control system requires development of control logic, which will minimize the interactions between control loops. To perform the logic functions, all the basic control functions like feedback (closed loop), feedforward (open loop), cascade and ratio are used individually and linked together in any needed combination. (Dukelow, 1995 pp. 3)

3.2.1.1 Feedback Control

In the feedback control, the changes in the primary variable are measured and fed back to a control function. The controller includes an error detection function, which measures the error between the primary variable and the set point. (Dukelow, 1995 pp. 41) In the block diagram of the Figure 22 is shown the basic feedback loop. The control loop is closed when a change in the controller output is fed to the controller to reduce the detected error and to bring the output of the system to a desired value. The advantage of the feedback is that the system tolerates external disturbances and internal variations in the system parameters. The major problem with the feedback is stability. A control system with feedback may tend to overcorrect errors, which can cause oscillations of constant or changing amplitude. (Ogata 1997, pp. 6-7) In several processes, the effect of the control parameter on the primary variable appears after a while. This causes a problem when a simple feedback circuit is used because in that case it tends to be too slow. (Lautala, 2001)

3.2.1.2 Feedforward Control

Feedforward control doesn’t use a measurement of the process variable to be controlled. Thus, the output of the system has no effect on the control action. The accuracy of the feedforward control system depends on the calibration. Feedforward control can be used, if the relationship between the input and output is known and there are neither internal nor external disturbances. If the disturbances are measurable, the disturbance-feedworward control can be used to cancel their effects on the system output. The measurable disturbances can be compensated before they materialize. This is an advantage, because in the feedback control system, the corrective action starts only after the output has been affected. Thus, the feedforward control is faster than feedback control. The feedforward system is easier to build than the feedback system because the stability is not a major problem. (Ogata, 1997 pp. 7, 700) Feedforward connection can be applied in the case where the time constant of the control variable is smaller than the time constant of the disturbance variable. Typically feedforward connection is applied together with the feedback. Feedforward connection is a common controller construction in industry. (Lautala, 2001)

3.2.1.3 Cascade Control

Cascade control consists of two feedback control loops connected together with the output of the primary loop acting as a set point for the secondary loop. In Figure 23 is shown the structure of the cascade controller.

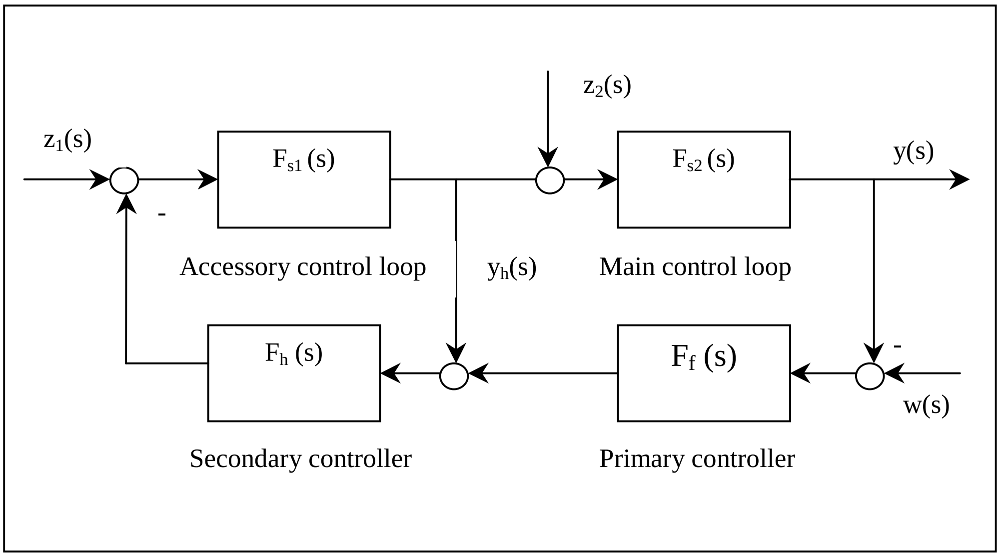


Figure 23. Structure of a cascade controller (modified from Schlitt, 1988 pp. 209)

A cascade controller is applied to stabilize the manipulated variable so that a predictable relationship between the manipulated variable and the primary variable can be maintained. (Dukelow, 1995 pp. 46) The control result can be approved with the cascade circuit, if it is possible to measure such parameters, which show the effect of the control variable or the disturbances earlier than the primary parameter. This means that the disturbances in the earlier phases of the process can be eliminated before they affect the primary variable. (Lautala, 2001) It is necessary that the response time constants of two feedback loops are substantially different to avoid the control instability between them. A general rule is that the time constant of primary loop process response should be a minimum of 5 to 10 times that of the secondary loop. (Dukelow, 1995 pp. 46) The most common combination is that the primary controller is of the PI-type and secondary controller is of the P-type. (Schlitt, 1988 pp. 210) A cascade control circuit is easy to tune and to understand. (Lautala, 2001)

3.2.1.4 Ratio Control

Ratio control includes a feedback controller whose set point is in direct proportion to an uncontrolled variable. The proportional relationship can be set by the process operator, or it can be automatically adjusted by another controller. If the ratio is set, the set point of the controlled variable changes in direct proportion to changes in the uncontrolled variable. (Dukelow, 1991 pp. 46-47) Ratio control is a special case of the feedforward control. (Lautala, 2001) In Figure 24 is shown an example about the ratio control.

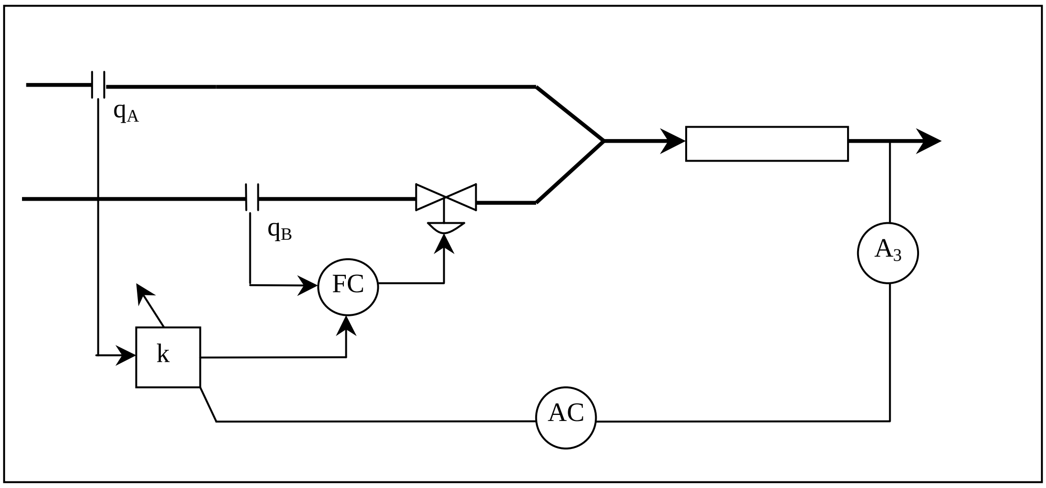


Figure 24. Ratio control, which is being updated with the feedback from the analyzer (Lautala, 2001)

3.2.2 Basic controllers

The most commonly used controllers in the feedback control circuits are PI and PID controllers. They consist of proportional (P), integrative (I) and derivative (D) parts. Controllers of this type are called linear continuous controllers. They have extensive application range and they are easy to tune. (Sinervo, 1997) and (Leiviskä, 1999 pp. 21)

P controller is a simple amplifier. The amplification of the P controller is linear and time independent. In general, it is applied as proportional part together with other controller types. The parallel combination of a P controller and I controller is the very common PI controller. (Sinervo, 1997) The step response of the PI controller is shown in Figure 25.

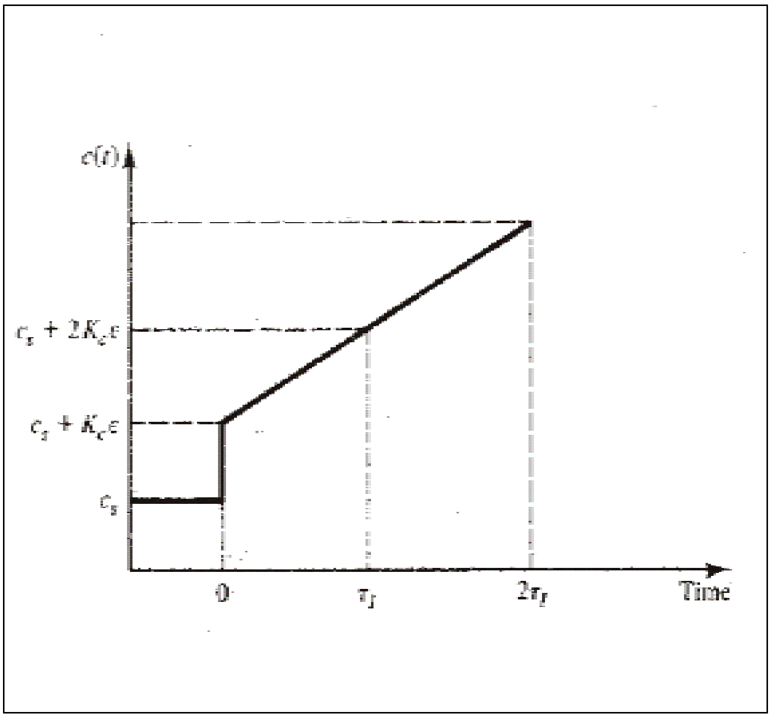


Figure 25. Step response of a PI-controller (Stephanopoulos, 1984 pp. 247)

The integral action causes the controller output to change as long as an error exists. Therefore, such a controller can eliminate even small errors. (Stephanopoulos, 1984 pp. 247) PI controller causes always a negative phase displacement, which has an undesirable effect on the system stability. A negative phase displacement reduces the critical frequency of the control system, which means that the bandwidth of the closed system is reduced and the control system will slow down. The pure derivative control is impossible, but the derivative effect can be combined with the P controller or PI controller. The step responses of the PD and PID controllers are shown in Figure 26.

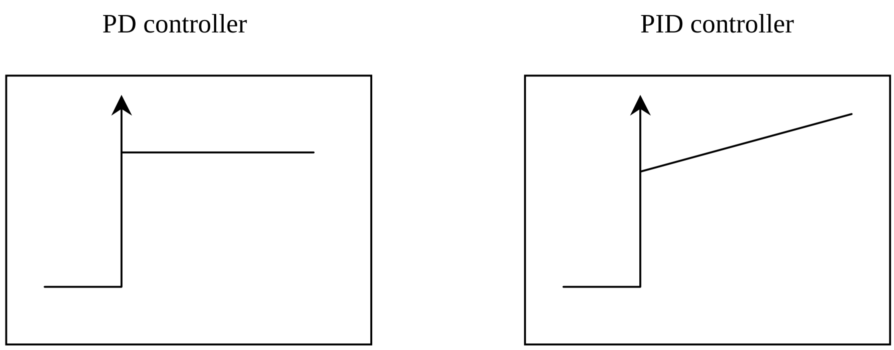


Figure 26. Step responses of PD and PID controller (modified from Sinervo, 1997)

PD controller causes a positive phase displacement, which increases the critical frequency together with the bandwidth of the closed system. This will speed up the control. (Sinervo, 1997)

PID controller combines the best characters of the PI and PD controllers. The I-part removes the permanent system deviation and the D-part creates a positive phase displacement in the critical frequency area. (Sinervo, 1997) With the presence of the derivative term, the PID controller anticipates what the error will be in the immediate future and applies a control action, which is proportional to the current rate of change in the error. (Stephanopoulos, 1984, pp. 248) A satisfactory PID control solution can be reached in the frequency band when the phase displacement with the open system is greater -180º. (Lautala, 2000, pp. 10-11) The critical frequency of the system is the frequency when the phase displacement is -180º. In Figure 27 is illustrated a simulation about the differences between the PI and PID controllers.

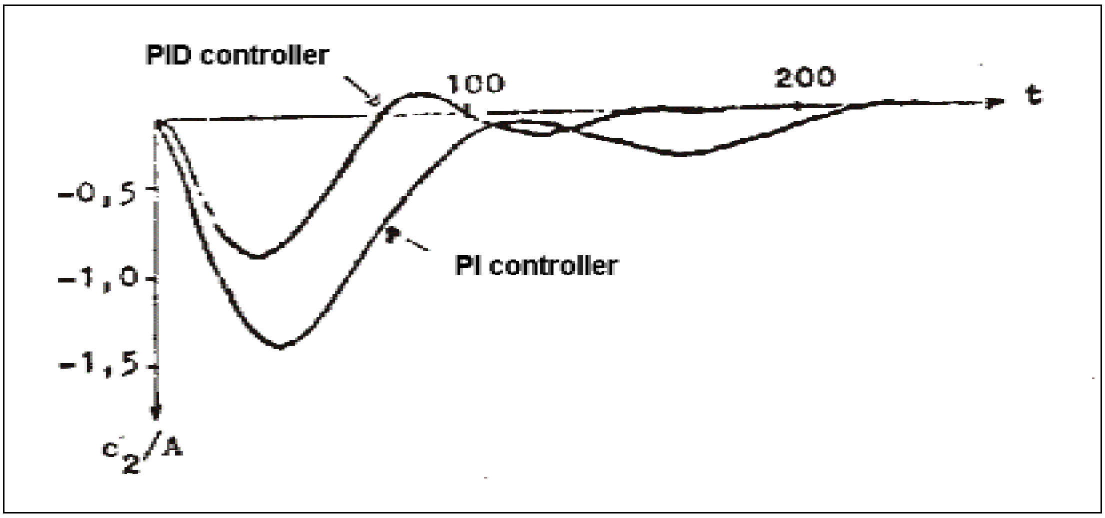


Figure 27. Simulation about the differences between PI and PID controller. (Sinervo, 1997)

From the Figure 27 it can be seen that a PID controller compensates the disturbance faster than a PI controller. The PID control is a linear control method, and it gives a satisfactory control solution with the reasonable amount of work including planning and introduction. (Majanne, 2000, pp. 3)

3.2.3 Dead Time Compensation

Significant dead time of the feedback control is a significant source of instability for the control system. For example the following situations increase the dead time of the feedback control: the process involves transportation of fluids over long distances or includes phenomena with long incubation periods, the measuring device like gas chromatograph requires long periods for completing the sampling and the analysis of the measured output, the final control element needs some time to develop the actuating signal or the human decision making needs significant time to think and take the proper control action. In these situations, the feedback control would provide unsatisfactory closed-loop response because the control action attempts to eliminate an error that originated awhile back in time. (Stephanopoulos, 1984, pp. 383-384)

A classical feedback system used for the compensation of dead time is called Smith predictor. In Figure 28 is shown the block diagramm of a Smith predictor.

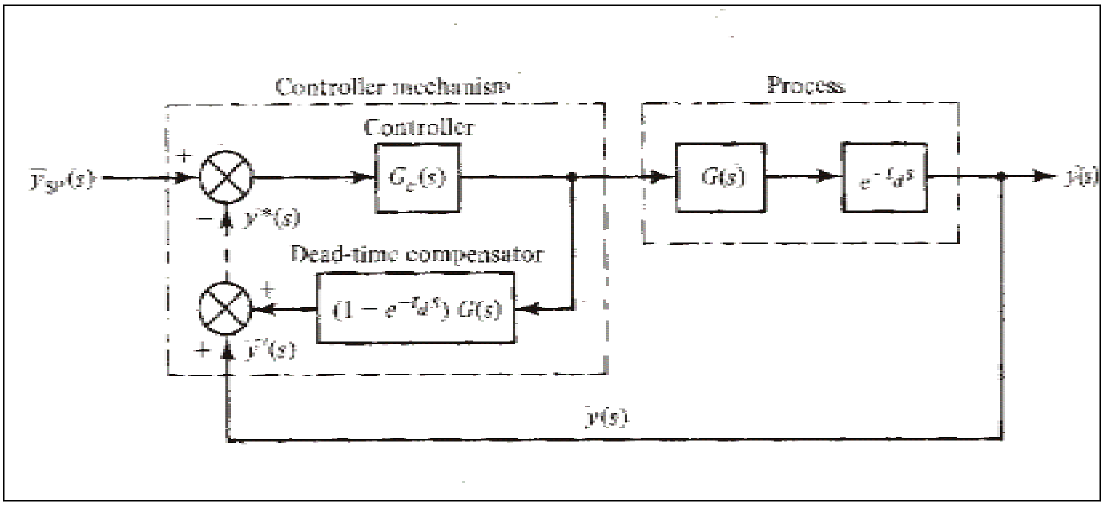


Figure 28. Smith predictor (Stephanopoulos, 1984, pp. 386)

A Smith predictor is a first-order dynamic model to predict the current value of the process variable based on the past values of the control output. Any difference between the predicted and the actual process variable is an indication of a process disturbance and requires a change in the controller output. (Karppanen, 2000a, pp.64) The dead-time compensator predicts the delayed effect that the manipulated variable has on the process output. This prediction is possible only if there is a model for the dynamics of the process. Thus, we need the transfer function and the dead time of the process for the dead time compensation. (Stephanopoulos, 1984, pp. 387)

3.3 Advanced Control Methods

Power plant processes have special features, which make the use of the traditional PID control circuits difficult. Traditional control methods are linear, while the power plant process behaves nonlinearly because of the heat transfer and asymmetric dynamics. The functional area of a PID controller is narrow and the controller must be tuned to react slowly to prevent the stability problems like responses to the wrong direction. Because of the fouling and fuel properties, the power plant process is time-variant. A scalar controller is not applicable to a multivariable process, where several cross actions disturb the process causing oscillations. This leads to problems with the tuning of the controller. Today, the demand for the efficiency and flexibility in energy production as well as emissions abatement, and such developments in power plant processes as higher load fluctuation velocities, require better control systems than before. Thus, the advanced control methods are needed instead of PID-based controllers. (Majanne, 2000, pp. 2-4)

Advanced control methods are considered as follows:

- optimizing control
- adaptive control
- model predictive control
- fuzzy control
- neural networks.

Another term relevant to the subject is soft computing, which includes fuzzy logic, neural networks, probabilistic reasoning, genetic algorithms and chaos theory. Methods of soft computing are considered intelligent and capable of learning. Other methods are left outside the definition, because the goal of soft computing methods is to mimic the linguistic human reasoning process in the computer environment. (Lautala, 2000, pp. 6) and (Carlsson et al., 1998)

3.3.1 Optimizing Control

Optimizing control refers to LQ (Linear Quadratic) control or other optimizing methods like optimization of the PID controller’s parameters. In both optimization tasks, the degree of the success can be measured with the integrals or sums of the adjustment error and control deviation. (Lautala, 2000, pp. 9) A Linear Quadratic Problem (LQP) leads to a control law of the same structure as the state-feedback controller. The problem is to minimize a criterion, which is a quadratic function of the states and the control signals. (Åström & Wittenmark, 1997 pp. 408) In Figure 29 is illustrated the principle of a state-feedback controller.

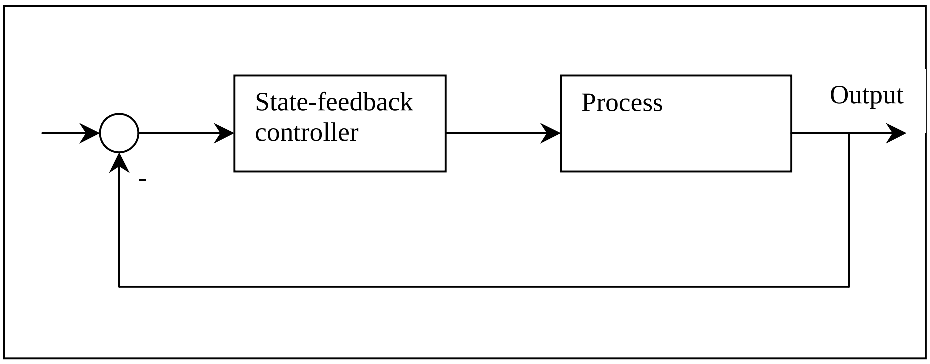


Figure 29. Block diagram of a state feedback controller (modified from Lautala, 2000, pp. 10)

In the optimizing control, the aim is to minimize the cost function

$$J = \sum_{j=1}^{n} S_j \tilde{J} + \sum_{j=1}^{n} Q_j J + \sum_{j=1}^{n} R_j \bar{J} \qquad (14)$$

of the linear system

$$\dot{x}(t) = Ax(t) + Bu(t). \qquad (15)$$

Optimizing control is based on the linear and reliable model of the optimized system. It is dependent on the initial value of state and on the set value, which may cause problems regarding output-feedback and optimal PID control. Quadratic optimizing control can be used to tune the multi-variable control, and it can be seen as a method to reduce the amount of parameters involved. Applying of optimizing control requires a large amount of work, which can be reduced with the use of a proper software. Maintaining the optimizing control requires continuous technical support from the developer. The optimizing control is applicable only when there is a reliable and robust model of the optimized process available. It should not be applied if the process is under a constant change, or there are only few measurements available in relation to the complexity of the process. (Lautala, 2000, pp. 11-15)

3.3.2 Adaptive Control

An adaptive control system is capable of modifying its own operation to achieve the best possible mode of operation. This implies that adaptive control system has the following features:

a) Providing continuous information about the present state of the system or identifying the process
b) Comparing present system performance to the desired optimum performance
c) Making decisions to change the system to achieve the defined optimum
d) Initiating a proper modification to drive the control system to the optimum

Identification, decision and modification are inherent in any adaptive system. (Thompson, 1998) In Figure 30 is shown the block diagram of an adaptive controller.

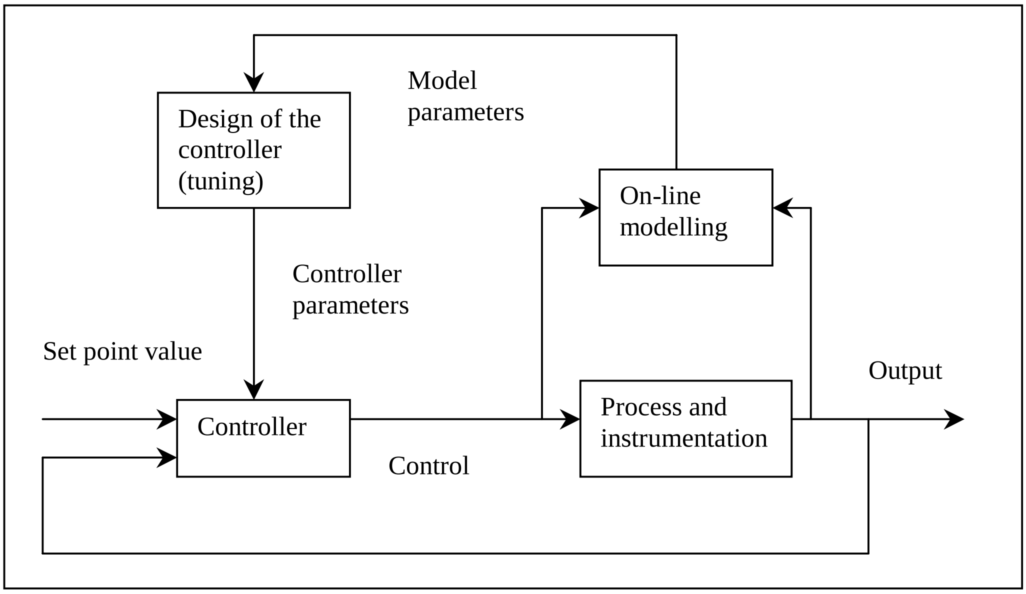


Figure 30. Adaptive self-tuning controller (modified from Lautala, 2000, pp. 17)

Different control methods, which are included in adaptive methods, are for example gain scheduling, self-tuning control and model reference control. Adaptive control can be applied especially in the control of strongly nonlinear processes. Also time independent processes, unknown processes, dead time processes and processes with strong interactions can require adaptive features from controllers. (Leiviskä, 1999 pp. 24-25) Successful long-time use of the adaptive controller requires a monitoring system, which is hierarchically placed above the controller. Adaptive controller is responsive to measuring errors, because the modeling, design and operation of the controller are based on the measurements from the process. (Lautala, 2000, pp. 18-21)

3.3.3 Model Predictive Control

The importance of the process model is especially emphasized in the modern process control. In the non-linear processes their role is significant. In model predictive control (MPC), a model of the process is used to predict the process output with given inputs over the prediction horizon. A criterion function is minimized in order to obtain the optimal controller output sequence over the predicted horizon. A predictive controller calculates such a future controller sequence that the predicted output of the process is close to the desired process output. Predictive controllers use the principle of receding horizon. Only the first element of the controller output sequence is applied to the control process. The whole procedure is repeated at the next sample. (Ikonen & Najim, 2001 pp. 180-181) In Figure 31 is presented the principle of the model predictive control.

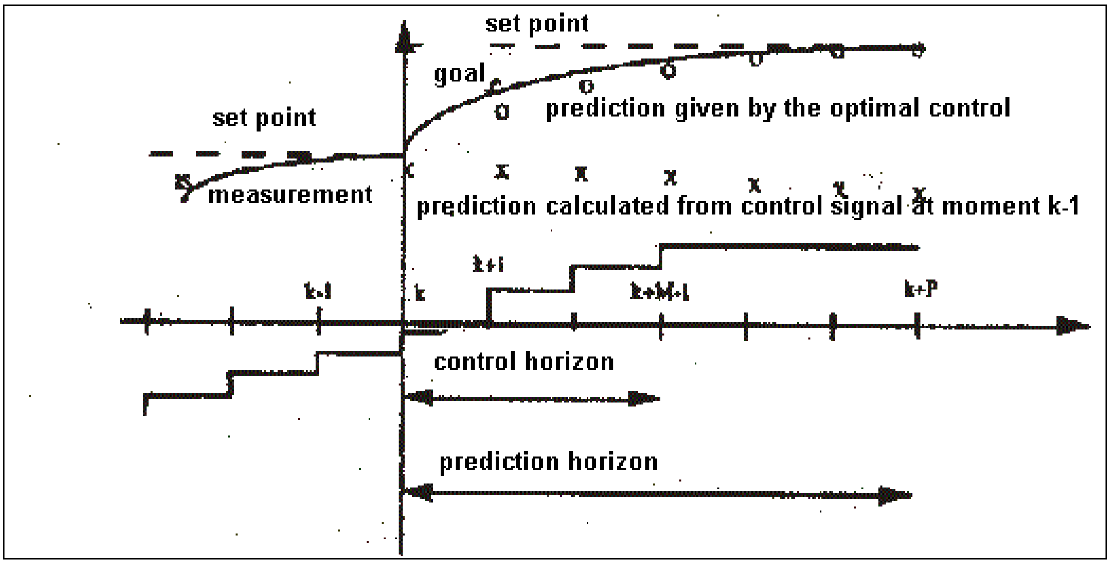


Figure 31. Principle of the model predictive control (Majanne, 2000 pp. 12)

MPC includes three main components, which are the process model, calculation of the optimal process control and a cost function. Predictive controller can be applied to the multivariable control and it operates feedforward if the model is perfect. If the process model and the output have a deviation, the feedback and feedforward are combined in the controller. (Majanne, 2000 pp. 12-13 and Mäkilä, 2000) The resulting control is linear and time-invariant if the model is time-invariant. (Ikonen & Najim, 2001 pp. 183) In the MPC control, the time constants can be taken into account and the restrictions can be included in the model. Problems can occur in the analysis of the closed system and in the evaluation of the model quality. (Lautala, 2000, pp. 24)

3.3.4 Fuzzy logic

Theory of fuzzy systems deals with the vagueness of real life. In science, the bivalent logic, which gives only two options, is preferred. This means that an object is able to belong to one set only. In fuzzy logic, the object is able to belong partly to a set. This enables the use of vague linguistic rules. In an old story, only one barber worked in a little village and he thought that he could divide all the men in the village in two categories. These categories were those who he shaved and those who shaved themselves. He just couldn't decide in which set he belonged to. With the theory of fuzzy sets, this question can be solved. (Carlsson et al. 1997)

3.3.4.1 Fuzzy reasoning

In the beginning, the concept of a fuzzy set must be introduced. A classical set fully includes or excludes any given element. Fuzzy set is a set without a clearly defined boundary. It can contain elements with only a partial degree of membership. Following statement is the foundation of the fuzzy logic:

In fuzzy logic, the truth of any statement is a matter of degree.

If statement "true" has a value of 1 and "false" a value of 0, fuzzy logic permits in-between values like 0,7. This describes the degree to which the element fulfils the measures of a full membership. A membership function (MF) deals with fuzzy sets, as it maps each input value to its appropriate membership value between 0 and 1. Membership functions have different forms, such as triangular, trapezoidal, Gaussian curve and bell-shaped types. In Figure 32 are presented some common types of the membership functions.

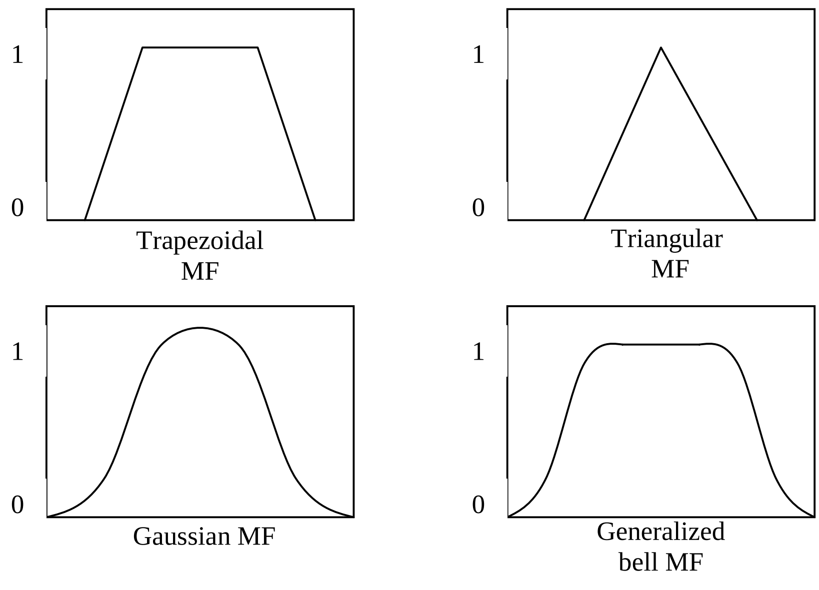


Figure 32. Different types of the membership functions (modified from Mathworks Inc., 1998a, pp.10-11)

In fuzzy control, the most popular shapes of membership functions are trapezoid and triangle. Basic logical operations are defined for fuzzy sets. Intersection is realized with min-operation and union with max-operation. Complement is also defined in these operations. The most common interpretations for the logical operations are so-called t-norms. They will meet the following basic requirements:

$$
\begin{aligned}
&T(0,0) = 0 \\
&T(a,1) = T(1,a) = a \\
&T(a,b) =\leq T(c,d) \; if \;\; a \leq c \;\; ja \; b \leq d \; . \\
&T(a,b) = T(b,a) \\
&T(a,T(b,c)) = T(T(a,b),c)
\end{aligned}
\qquad (16)
$$

The fuzzy rule base consists of if-then rules, which formulate the conditional statements like: if x is A then y is B. The if-part is called antecedent, and the then-part is called consequent. They both can have multiple parts. If antecedent has multiple parts, are all the parts calculated simultaneously and resolved to a single number with logical operations. The parts of the fuzzy system are presented in Figure 33.

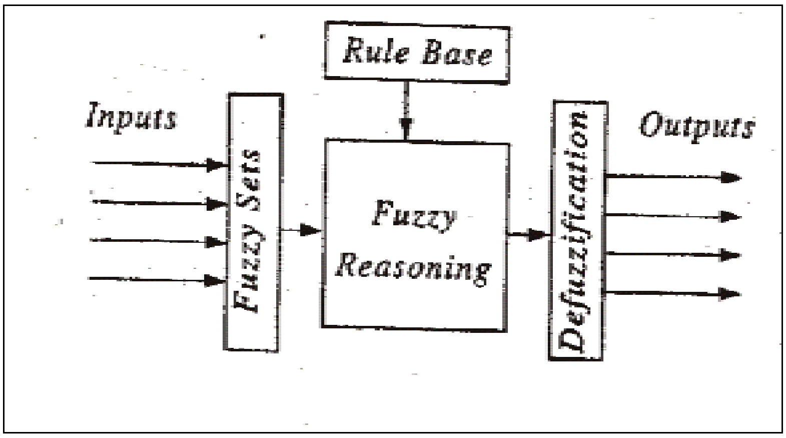


Figure 33. A fuzzy system (Majanne, 2000, pp. 17)

First step in a fuzzy system is to fuzzify the inputs, which means resolving all the parts of the antecedent to a degree of membership between 0 and 1. Second step is to apply fuzzy operators and fuzzy inference. Third step is to defuzzify outputs. The most popular method is the mass centroid calculation, which returns the center of area under the curve. The other corresponding methods are bisector, middle of maximum, largest of maximum and smallest of maximum. (Mathworks Inc., 1998a pp. 4-28), (Juuso, 1997 pp. 14-27)

3.3.4.2 Advantages of Fuzzy Logic

The following reasons support the use of fuzzy logic in the computer environment:

1) Human reasoning can be described better with fuzzy systems.
   Fuzzy logic is based on natural human language, which allows the use of vague expressions such as about five, almost between, rather hot and quite young.

2) Building, using, applying, understanding and teaching fuzzy systems is easy.
   Especially nonlinear systems cannot be described with a mathematical model, or the mathematical model for the system is too complex. Fuzzy logic can model nonlinear functions of arbitrary complexity. The mathematics behind the fuzzy reasoning is very simple. The systems created with the fuzzy logic are user-friendly.

3) Fuzzy systems can be easily automated.
   Fuzzy systems are programmable and they require less storage space than conventional methods. Fuzzy solutions are faster, cheaper and more reliable than conventional solutions.

4) Fuzzy systems are versatile and they have numerous solutions.
   Almost any system can be fuzzified, and it can be more easily utilized after the fuzzification. Everything is imprecise if it is looked closely enough, and fuzzy reasoning builds this understanding into the process. (Carlsson et al. 1998)

3.3.4.3 Applying fuzzy logic

Fuzzy logic has been applied in areas such as diagnostics, optimization, robotics, mathematics, decision-making, control, sociology and behavioral science. The most successful application of fuzzy logic is fuzzy control. It has proved to be an efficient method to improve the function of the conventional control systems. Following figure presents the different roles of fuzzy logic in process control.

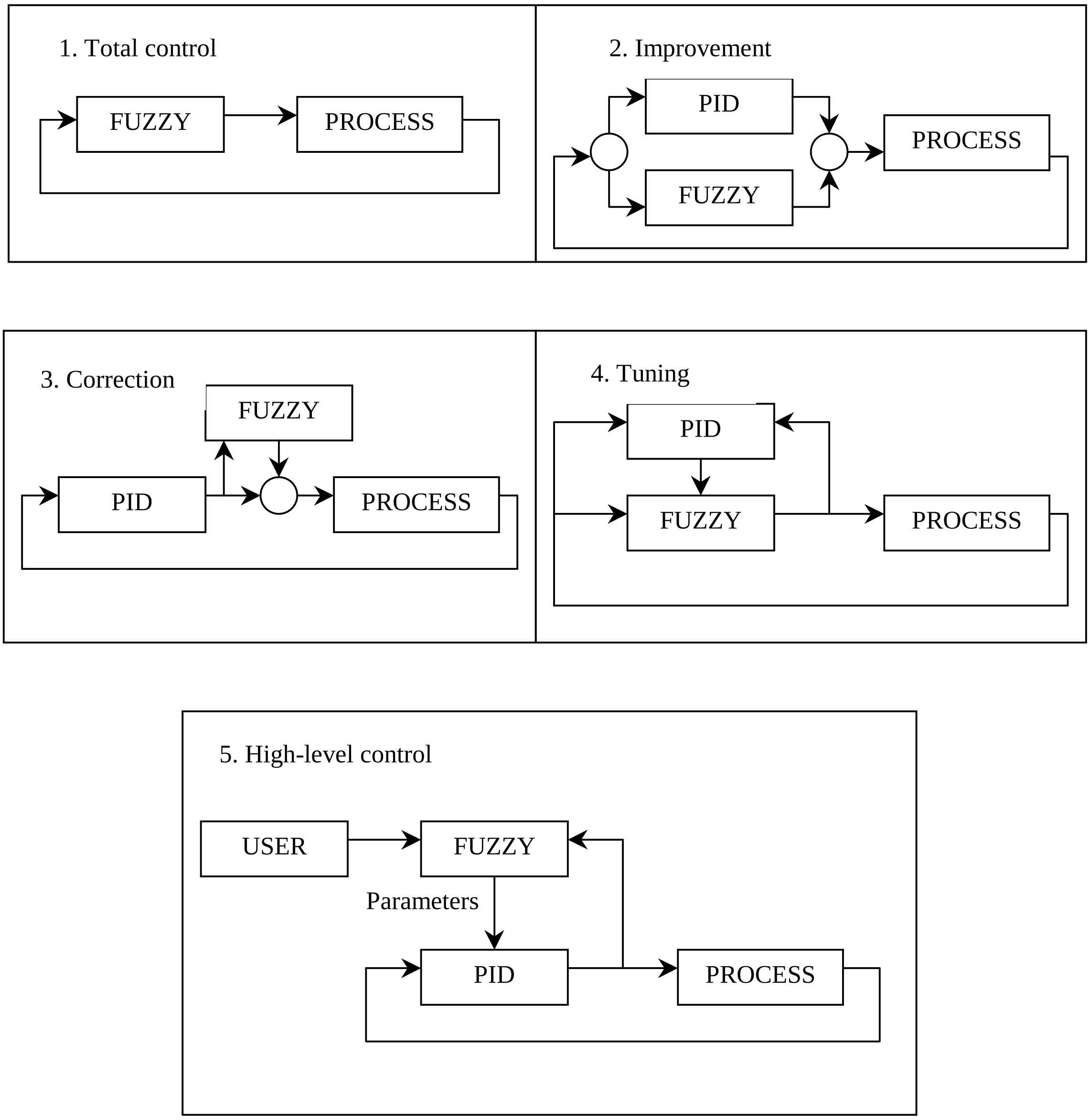


Figure 34. Roles of fuzzy logic in process control (modified from Carlsson et al. 1998)

Fuzzy control should be applied in such cases which can’t be solved with the conventional methods. Appropriate cases for the use of fuzzy logic can be as follows:

1. Non-linear and time-variant problems: The dead time of the process is significant or process includes random disturbances
2. Mathematical model of the process is hard to formulate or to understand
3. Updating frequency of measurements and analysis results varies with time
4. There is some heuristic information about the process and it is difficult to model.

The following list contains some additional advantages, which fuzzy control can offer when it is compared with conventional methods.

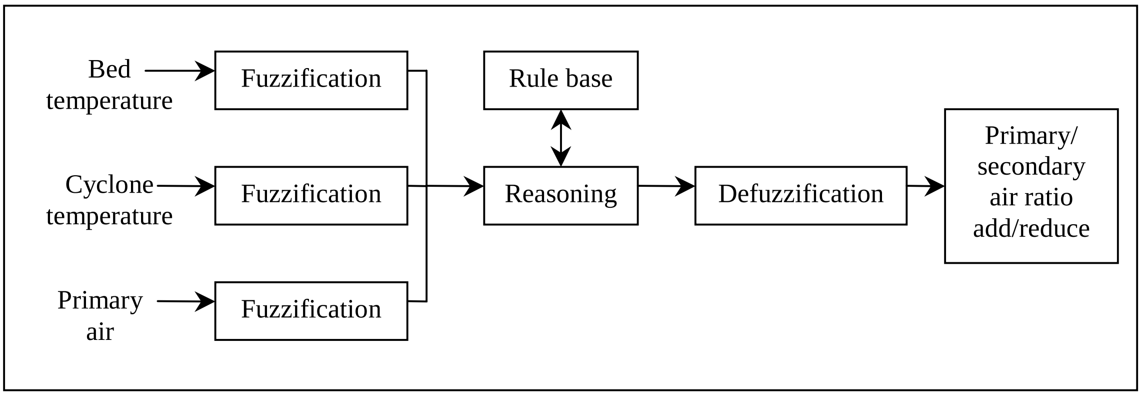
1. Lower energy consumption by more precise control
2. Better and more uniform quality by robustness of the fuzzy control
3. Simplified production/control process.
   Performance remains the same or even improves with the decreased amount of sensors.
4. Faster development of control applications
5. Lower material/component costs
6. Simpler maintenance
7. More rational use of human resources
   Higher automation rate leaves more time to concentrate on more demanding tasks.

There are also certain problems related to fuzzy control. Knowledge acquisition can turn out to be difficult as information must be collected from the specialists. It is possible that a person, who knows what to do in certain situations, doesn’t know or can’t speak out why he does so. More problems can emerge when the controller must be tuned. There are no systematic methods to tune a fuzzy controller. This leads to the use of the attempt and fail –tuning method, which is difficult and time-consuming. It is possible to reach a moderate control result without bigger problems, but reaching an optimal control result may turn out to be almost impossible. Tuning of the fuzzy controller is particularly difficult when the fuzzy rule base is large. In the case of fuzzy control, it is difficult to prove that the performance of the controller is optimal and stable. (Carlsson et al. 1998), (Mathworks, 1998a pp. 5-6)

3.3.4.4 Fuzzy Control of CFB Boiler

There are few applications of fuzzy logic to be found for fluidized bed boiler. In Finland, exist so far only four power plants, which have applied fuzzy solutions to CFB boiler control. Automation suppliers have their own fuzzy concepts, which can be used in CFB boilers. Power plant owners are not very eager to invest in automation, although significant benefits could be achieved with moderate efforts. As a rule of thumb, it can be said that advanced control methods are applied to CFB boilers only if the boiler is big enough or it has operational problems. (Karppanen, 2000b) and (Pyykkö, 2000)

Neles Automation has introduced a fuzzy logic control for fluidized bed boilers. It includes the control of total air amount, control of bed temperature, control of temperatures in the upper furnace and cyclones, control of combustion symmetry, optimization of O_2/CO ratio in flue gas and control of emissions in the flue gas. In Figure 35 is presented a control solution for the bed and cyclone temperatures.



Fuzzification of the bed temperature

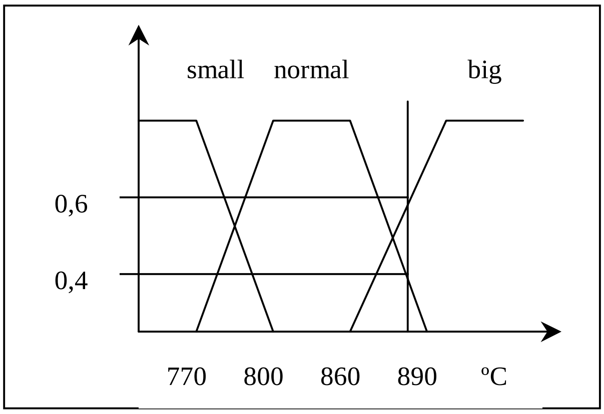


Figure 35. Fuzzy control of bed and cyclone temperatures (modified from Pyykkö, 2000)

The goal in the use of fuzzy applications is to improve the boiler efficiency, to control the emissions and to gain cost savings. The first Finnish application of fuzzy control was the fuzzy combustion control at Rovaniemi power plant in 1997. Following results were gained with the application of fuzzy control: combustion air control was improved, bed temperature deviation was decreased and previous manual control was replaced by automatic control actions. (Neles Automation, 2001) and (Pyykkö, 2000)

Erkki Karppanen from Honeywell has written in his doctoral thesis about the fuzzy control of a CFB boiler. The goal was to seek solutions for control problems of a multi-fuel CFB boiler. Following solutions were developed: control of steam pressure, compensation of fuel quality fluctuation, fuel-feed optimization and increased bed fuel inventory monitoring. The case was dealing with the multi-fuel CFB boiler K6 in Varenso power plant. K6 supplies steam to Stora Enso Varkaus Mill and it is a swing boiler Thus, the load changes in the steam net must be compensated by controlling the fuel feed of the K6. Fuel contains mostly wood waste, coal is used as the auxiliary fuel. Control applications were first tested in the R&D center of Foster Wheeler in Karhula. Thanks to the tests, the installation of the control applications at the Varenso power plant was plainly easier.

Steam pressure control of K6 is realized with a pressure-based fuzzy logic controller in which the control output is corrected with a term derived from the steam flow and from the steam pressure change. Steam pressure control is integrated into a fuel-feed optimization block, which includes also a fuzzy compensation of the fuel quality fluctuation. In Figure 36 is presented the function principle of fuel-feed optimization.

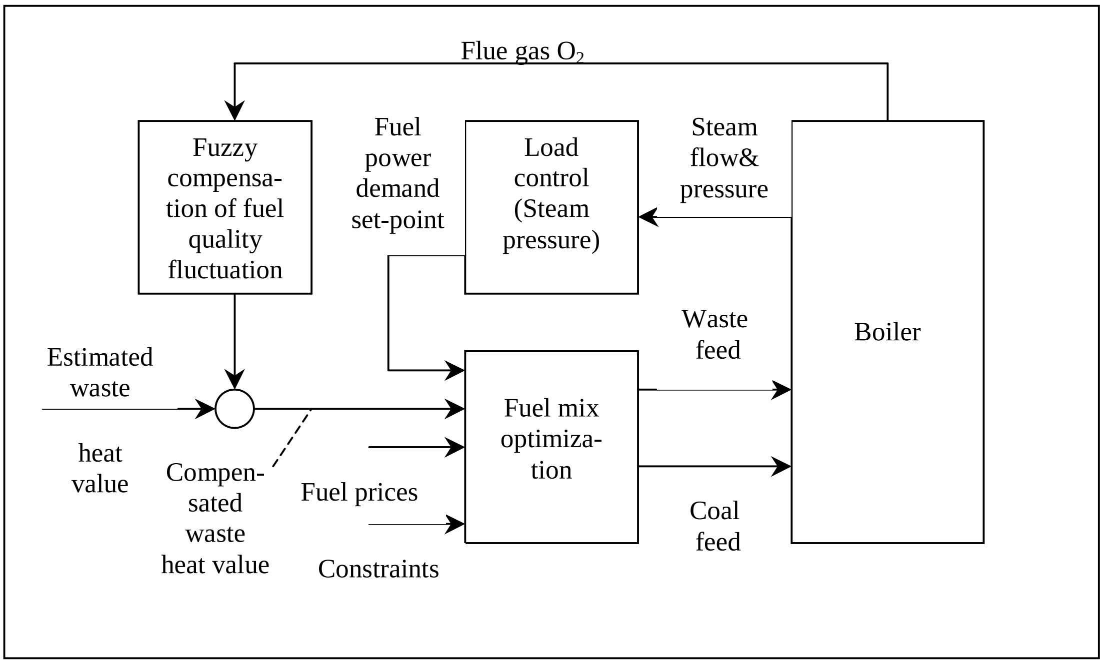


Figure 36. Principle of fuel-feed optimization (modified from Karppanen, 2000a, pp.90)

Fuel feed optimization is not actually a fuzzy solution, since it resolves settings for waste feed and coal feed so that the total feed equals power set-point, and the cost function reaches it's minimum simultaneously. The solution for increased fuel inventory monitoring is based on fuzzy decision making. A control problem appears if coal (char) inventory increases dramatically in the bed, which may cause sintering of the bed material.

In the steam pressure control, the fuzzy logic controller seems to perform much better than the conventional PID control during a long operation period. In Figure 37 is presented the difference between PID control and fuzzy control in steam pressure control.

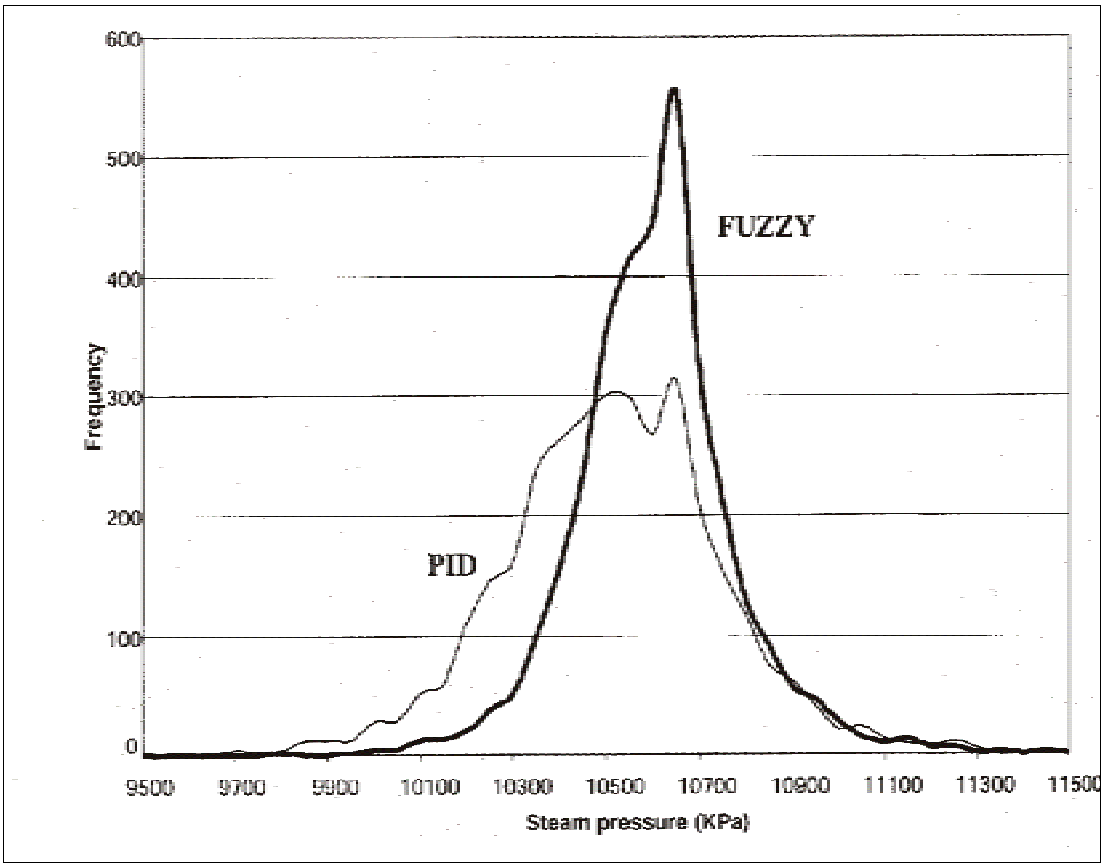


Figure 37. Steam pressure histogram with PID control and fuzzy control (Karppanen, 2000a, pp.108)

The steam pressure controller is not very robust, because it should have been re-tuned when steam accumulator was not in use. Tuning is generally done by using trial-and-error method. More recommendable method is the use of tuning grips, which means for example that the gain of the fuzzy logic control can be changed by changing one parameter at the time and the influence on all fuzzification or defuzzification parameters is similar.

Compensation of fuel quality fluctuation with the fuzzy control gives its best performance when it is built as nonlinear. The waste fuel heating value cannot be calculated reliably enough for control purposes. It is replaced with fixed average of the waste fuel heating value. Fuel-feed optimization has succeeded in reducing the fuel costs. Coal consumption is dramatically reduced at the power plant. The whole project has proven that fuzzy logic works appropriately in control solutions, but it is worth paying attention to logical operators used, because information can be lost due to too cutting connective operators. Following advantages of fuzzy control were reported: lower fuel costs, higher boiler efficiency, lower heat stress, lower emissions and improved availability. (Karppanen, 1998 pp. 22-26) and (Karppanen, 2000a, pp. 81-127)

3.3.5 Neural Network

The basic idea of a neural network is to imitate the human nervous system. The human brain is a complex, nonlinear and parallel information-processing system, which has a staggering number of neurons with massive interconnections between them. A developing nervous system is able to adapt to its surroundings by creating the new synaptic connections between neurons or by modifying the existing synapses. Neural networks are made of artificial neurons, which have multiple input and one output. Neural networks are trained so that a particular input leads to a specific target output. Neural networks are considered as an intelligent method, because they are able to learn the solutions from examples, and to adjust the solutions to situations not encountered during the training. (Haykin, 1994 pp. 1-3), (Koikkalainen, 1994, pp. 6-7) and (Mathworks Inc., 1998b, pp. 2-3)

3.3.5.1 Basic Concepts of Neural Network

A single neuron is an information-processing unit, which behaves like a function. Neurons convert an unbounded input activation to a bounded output signal. The model of a neuron is shown in Figure 38.

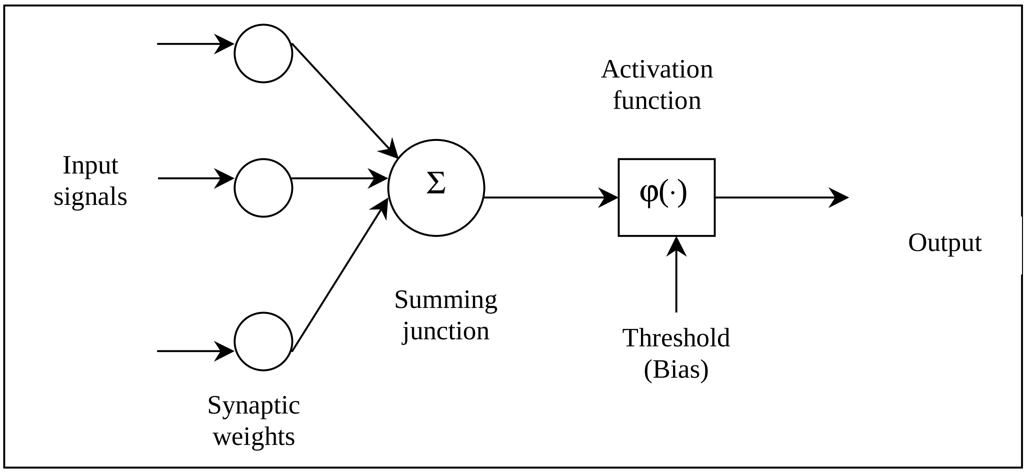


Figure 38. Nonlinear model of a neuron (modified from Haykin, 1994, pp. 8)

Neurons have synapses, which are in other words connecting links between neurons. Connection is mostly feedforward, but feedback connections are also possible. The inputs of the synapses connected to neurons are multiplied by the synaptic weights. If the weight is positive, the associated synapsis is excitatory, and if the weight is negative, the associated synapsis is inhibitory. A summing junction sums the weighed input signals. An activation function gives the response of a neuron. It limits the amplitude of the output to a permissible amplitude range. The externally applied threshold, which is also known as bias or offset, has a capability to lower the net input of the activation function. The most common form of activation function is the sigmoid function shown in Figure 39.

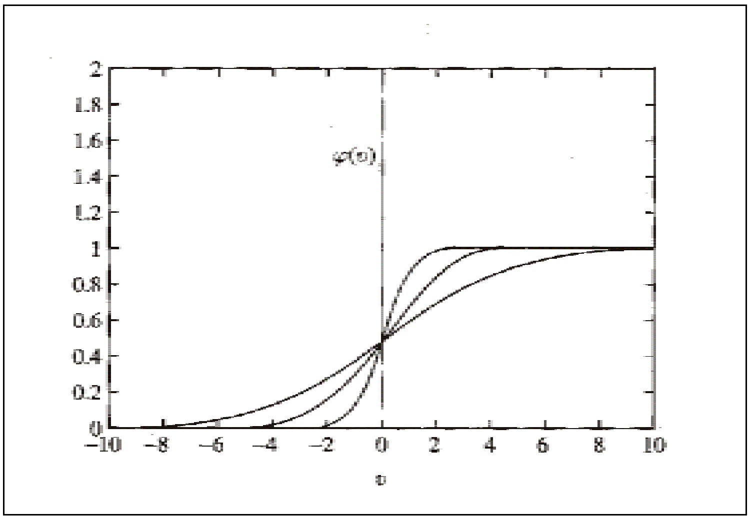


Figure 39. Sigmoid function (Haykin, 1992, pp. 11)

Neural network can be organized to different architectures, which are linked with learning algorithms used to train the network. The structure of the neural net determines how information is transferred between neurons. The simplest form is a layered network, which has only input layer of source nodes. The input layer projects onto an output layer of neurons. Multilayer network contains one or more hidden layers, which intervene between the external input and the network output. In Figure 40 is presented the structure of a multilayer network.

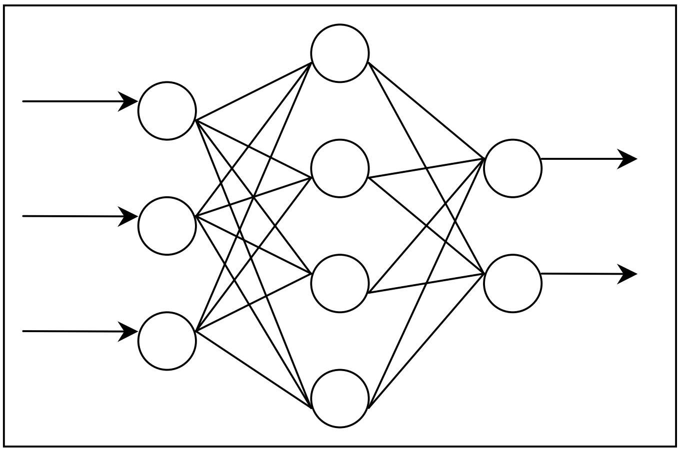


Figure 40. Multilayer network (modified from Haykin, 1994, pp. 141 and Lautala, 2000, pp. 36)

This structure is also known as multilayer perceptron, and it is the most common structure used at the moment. Input of the neural net is presented in a form of vertical vector, which is multiplied with weight matrix. The result is a vertical vector, which can be used as input for the next layer.

Neural net has an ability to learn from its environment and to improve its performance through learning. In the learning process, the synaptic weights and thresholds are adjusted iteratively through stimulation by the environment. The sample data changes the system parameters, and in a simplified form, learning means any change in any synapse. The algorithms of neurocomputing have three basic classes: supervised learning, reinforcement learning and self-organized learning. In supervised learning, the neural net is taught to calculate the outputs with certain inputs. It requires an external teacher, and the result is a generalized formula, which expresses how to respond to certain input. Learning algorithms of the supervised learning include least-mean-square algorithm and its generalization known as backpropagation algorithm. Supervised learning can be performed either off-line or on-line. The limitation of supervised learning is that it cannot learn new strategies without a teacher.

In reinforcement learning, the learning happens through the process of trial and error. In nonassociative reinforcement learning, the reinforcement is the only input received from the environment. In associative reinforcement learning, the environment provides additional forms of information other than reinforcement. Reinforcement learning is an on-line learning process. In unsupervised learning, there are no specific examples of the function to be learned. It is also referred as self-organization, which means that regularities will be searched from input values. They can be used in interpretation of the input data. In the teaching algorithm, neurons are competing of which neurons represent each of the given inputs best. This is called competitive learning. The main idea is that no piece of information will be lost in calculation, and the input can be restored as near to the original as possible.

Generalization means the ability of neural net to return a reasonable response to the inputs, which are not included in a training set. Neural network is useful only when generalization is needed. Otherwise, the capacity of a normal computer is sufficient for solving the problem. In overtraining, the training set is too small, and the neural net is able to learn almost the whole training set, and it will lose its ability to generalize. The capacity of neural net is related to the amount of its synaptic weights. The more synaptic weights there are, the better the learning capability of neural net is. Thus, the amount of synaptic weights must be carefully considered to avoid overtraining and simultaneously to maintain the learning capability. (Haykin, 1994, pp. 8-11), (Juuso, 2000, pp. 87-95), (Koikkalainen, 1994, pp. 32-34) and (Kosko, 1992, pp. 39-43)

3.3.5.2 Advantages of Neural Network

As discussed before, the neural network derives its computing power through its parallel distributed structure and its ability to learn and generalize. Therefore, it is able to solve complex problems, which do not have a mathematical model. The use of neural network offers following benefits:

1. Nonlinearity
   Neural network is able to deal with nonlinear correlations of the real world.
2. Generalization
3. Adaptivity
   Neural networks have capability to adapt their synaptic weights to changes in the surroundings. They are able to perform robust in a nonstationary environment.
4. Fault tolerance
   The conflicts between input values are tolerated, and with the help of the neural network the most reliable solution can be chosen. Neural network is also able to operate although a part of it is damaged.
5. VLSI Implementability
   The massive parallel computation capability makes the neural network suitable for implementation of very-large-scale-integrated technology. Neural net is able to capture truly complex behavior in a highly hierarchical fashion. This makes it a suitable tool for applications involving pattern recognition, signal processing and control.
6. Uniformity of analysis and design
   Neural networks are universal information processors. A neuron is a common ingredient of all neural networks, which makes it possible to share theories and learning algorithms in different applications.

There are also certain problems in applying of neural networks. The rules are formulated as synaptic weights, which makes their evaluation and explaining rather complex. The mistakes made in training data acquisition cannot be corrected later. Training data acquisition is the most critical phase in neural network design. Training phase requires a lot of work and computing capability. Designing and training of the application determines the quality of the final result. (Haykin, 1992, pp. 4-6), (Juuso, 2000, pp. 114-115) and (Koikkalainen, 1994, pp. 14-15)

3.3.5.3 Applying Neural Network

Solving of a new control problem should be started with linear models. If they are not applicable, local linear models should be tested next. If they cannot be applied the next step is to try with a simple nonlinear model. The last method to apply is a neural network. Neural nets are the most useful tools when the system cannot be mathematically modeled, when the system is strongly nonlinear or complicated, and when environmental factors are unknown or too difficult to add to the system. Neural nets are able to model complex inner correlations of data sets. This has brought many new applications, which have earlier been considered as impossible to calculate. The neurocomputing is at its best in modeling, and performs well in processing and interpretation of the measurement data. Neural nets are applicable also to optimization and estimation tasks. They have been applied for example in economic and statistic applications, pattern recognition and diagnostics.

In control applications, neural nets are essential in modeling of difficult processes. Neural network model is based on measurement data. Control applications using only neural nets are unusual. Mostly neural nets perform as a part of for example optimizing or adaptive control system. They can be used in pre- and postprocessing of the input and output data. Neural nets are included in so called intelligent methods, and they provide the control systems with artificial expertise and observation of unknown abnormalities. Machine vision and pattern recognition are used in robotics control, and at the moment, they are perhaps the best known area of neurocomputing. In economics, neural nets have made it possible to find correlations which have been considered not to exist. There is some potential for neural nets for example in logistics as well as in compression of speech and pictures. In diagnostics neural nets perform best together with expert systems. (Juuso, 2001, pp. 115-116), (Koikkalainen, 1994, pp. 37-78) and (Lautala, 2000)

3.3.5.4 Neural Network Models in Control Applications

Controllers containing neural nets can be divided into controllers based on inverse models, and into predictive controllers. Inverse model is trained off-line and placed into the control loop. In a simplest case, the model learns one nonlinear discontinuity state. In a predictive controller, a model generates the prediction. Neural network based models operate as a black box models. It means that they build their own models from the huge amount of process measurement data, and a mathematical model won't be needed. In practice, successful modeling requires a wide understanding of the process. (Jalkanen et al., 2000) and (Lautala, 2000, pp. 41)

Imatran Voima Oy and Taipale Engineering have studied the neural network -based optimization of fluidized bed combustion at the Rauhalahti power plant in Finland. The boiler at the power plant is a multi-fuel BFB boiler, and the aim of the study was to optimize the operating parameters of the boiler. The main questions were: can the flue gas losses be decreased, and can the NO_x amount be decreased, and whether these goals are in conflict. The boiler should be operated so that the costs are minimized, and the regulations are followed. Multilayer perceptron was used in modeling and it was trained with backpropagation method. Inputs were the flue gas temperature and the NO concentration in flue gas. Training was not stopped until the neural net could provide a result with acceptable error. Accuracy of the model was proven to be quite good. The result was that boiler performance could be improved with the optimization. Thus, neural net models can be applied in process tests when suitable operating parameters are sought. (Välisuo et al., 1995, pp.448-450)

Another boiler control application of neural nets is on-line optimization of a pulverized coal-fired boiler. The study was done by Fortum Engineering at the Naantali power plant in Finland. The aim was to improve boiler efficiency, to decrease NO_x emissions, and to control residual flows of the power plant. Multilayer perceptron structure was chosen for the neural net. It performed robust and its availability was good. NO_x emissions were optimized with air feed control. Boiler efficiency was optimized with minimization of the losses. The optimization application was able to adapt for changes for example in fuel quality. The adaptivity of the application was controlled with the least mean square estimation method. The optimization can be applied also in other projects. Only experimental part including data acquisition must be done again. The optimization can be integrated to process control system and operators can use it to determine the optimal operating parameters. Optimization performance is continuously observed and analyzed with remote monitoring. (Jalkanen, 2000) and (Jalkanen et al., 2000)

3.3.6 Hybrid Systems

Hybrid systems, also known as fuzzy-neural systems, are combinations of fuzzy inference systems and artificial neural networks. They are expected to sum the positive features of both methods. They deal efficiently with the two very distinct areas of information processing. Fuzzy sets are good at various aspects of uncertain knowledge representation, while neural networks are efficient parallel structures capable of learning from example. Fuzzy systems try to capture human thinking and reasoning capability at a cognitive level, and neural networks attempt to mimic the mechanism of a brain at the biological level. They can be discussed with a common language, particularly when they are employed in solving engineering problems. Both systems have also their weaknesses. Fuzzy sets cannot carry out learning and adaptation to a changing environment, and the role of neural networks in representing and handling uncertainty is fairly limited. Thus, these systems become complementary, in the sense that some features that are dominant in one approach are significantly lacking in the other. There is an evident interest in combining both fuzzy sets and neural networks in such applications as fuzzy control, pattern recognition and identification.

Fuzzy-neural control has following definitions: the controller has a structure resulting from combination of fuzzy systems and neural networks. The resulting control system consists of fuzzy systems and neural networks as independent components performing different tasks, or the design methodologies for constructing controllers are hybrid ones coming from ideas in fuzzy and neural control. First fuzzy-neural applications were realized in Japanese consumer electronics like refrigerators, washing machines, air conditioners and heaters. Fuzzy-neural systems are mainly used to speed up the development of fuzzy systems. The tuning of membership functions can be done with a neural network. Another common application is to adapt the control system to the changes in operating conditions.

In a hybrid neural network, the input values, synaptic weights and activation functions are explicit, but in the calculation of synaptic weights, T-norm, S-norm or compensating operators are used. All inputs, synaptic weights and outputs are real numbers between [0,1]. Information-processing unit of the hybrid neural network is called a fuzzy neuron. ANFIS-structure is an example of fuzzy-neural systems. ANFIS (Adaptive network based fuzzy inference system) has five different layers shown in Figure 41.

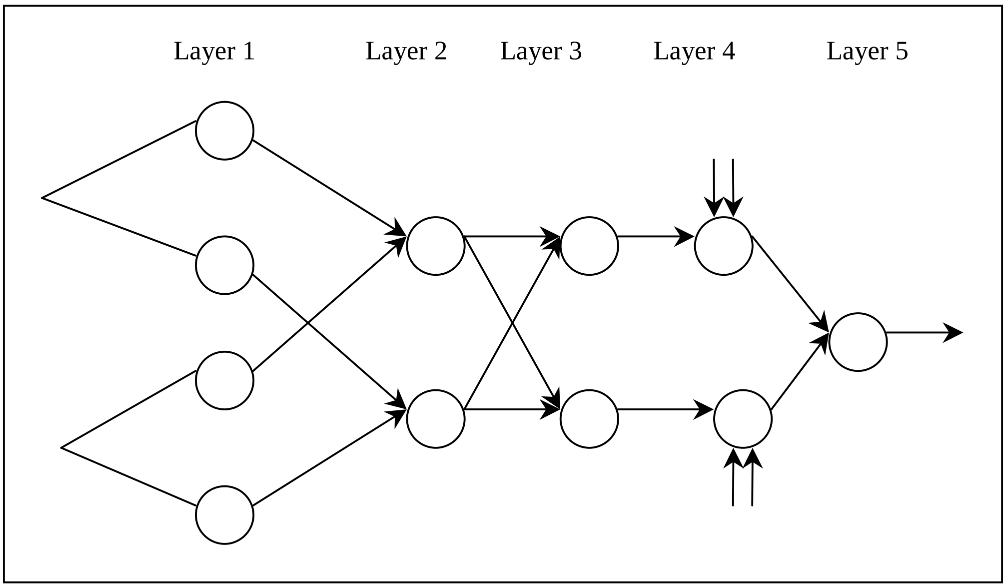


Figure 41. ANFIS-architecture (modified from Juuso, 2000, pp. 120)

Layer 1 is a fuzzification layer, and its parameters depend on the chosen membership function. Layer 2 counts degrees of membership for different rules to become operative, layer 3 normalizes degrees of rules to become operative, layer 4 calculates weighed responses and layer 5 calculates the final response of the network.

Parameters of the network are tuned with backpropagation method, and the tuning is observed with mean square error. This allows the fuzzy system to learn from the data it is modeling. ANFIS-method can be used to choose the membership function parameters automatically instead of just looking at the data. (Juuso, 2000, pp. 117-121), (MathWorks Inc., 1998a, pp. 76-77), (Nie & Linkens, 1995, pp. 155-158) and (Pedrycz, 1993, pp. 249-253)

3.4 Future Possibilities for Control of Fluidized Bed Boiler

The idea of the sustainable development creates new challenges for the boiler control. Environmental-friendly performance, efficiency, safety as well as economic and disturbance free use of the boiler are all pursued at the same time. This creates more challenging tasks in the boiler control, and more complicated control systems are needed. Automation degree of the boiler control increases continuously. Challenges for a CFB boiler control are to take into consideration the fuel quality and load changes in the air distribution control, to ensure the symmetry in the different parts of the boiler by balancing the amounts of the air and fuel, and to stabilize the combustion and reduce emissions by controlling the bed temperature. (Kinnunen, 2000, pp. 72-73)

Nowadays, control systems are implemented with digital control instead of analog applications, which makes the implementation by software of more complex algorithms much easier. The successful use of model-based control relies on the accurate boiler model that runs significantly faster than its real-time counterpart. The boiler model is connected to the system with same process inputs as the boiler itself, and a change in the inputs results in a rapid computation of model outputs that predict future process measurements values. Control actions will be corrected before the predicted deviations appear as real deviations. With model-based control success relies on the accuracy of the model. Therefore, the model should be able to learn and constantly improve itself as the environmental conditions change during the time. It should also be able to deal with imprecise process measurements. The expense of the model development and lack of system understanding of typical control engineering staff are the key drawbacks to the greater use of this kind of the systems. In every case, it must be shown that the improved control performance will pay increased costs. (Dukelow, 1991 pp. 397-398)

The development of information processing and computers has made it possible to apply advanced control methods also in the area of boiler control. The increased computing efficiency and cheaper hardware facilitate the use of complex model-based control systems. The best solutions in power plant use are expert systems, which make suggestions about the following procedures to the process controller. They can be also capable of simulating the effects of certain control procedures. Thus, the responsibility of the control actions remains with the process controller. (Pyrhönen, 2001)

4. AMMONIA FEEDING TESTS

Test equipment of ammonia feeding is located at the power plant of the Brista Kraft Ab in Sweden. Test equipment includes ammonia feeding equipment, ammonia feeding control system and process data acquisition. Ammonia feeding equipment is a part of the hybrid SNCR/SCR system for NO_x abatement.

4.1 Power Plant of Brista Kraft Ab

The power plant of Brista Kraft Ab is located in Sigtuna municipality in Sweden. The annual operational time of power plant called Bristaverket is about 5000 hours. The operational area of Brista Kraft Ab is energy production. It produces electricity for private customers and companies and district heating for the municipalities of Sigtuna and Upplands Väsby. Birka Energi Ab and Sigtuna Energi Ab are the owners of the company.

4.1.1 Description of the Power Plant

The power plant of the Brista Kraft Ab is combined heat and power (CHP) plant. It is equipped with 122 MW_{th} Foster Wheeler circulating fluidized bed boiler equipped with compact particle separators. The fuel for the power plant consists of forestry felling waste in the form of branches and tops, thinnings and wood damaged by rot and mildew. Forest industry byproducts like bark and sawdust are also mixed in the fuel. The fuel mix includes about 15 % sawdust, 45 % forest waste and 40 % bark.

4.1.1.1 Technical Data of the Power Plant

The power plant consists of a 122 MW CFB boiler and a 44 MW steam turbine divided into a high-pressure and a low-pressure part. The district heating water is warmed with the bled steam from the low-pressure part and with the back-pressure steam from the end of the turbine. Ratio of the produced electric power to the useful process heat is 0,57. The maximum steam flow of the CFB boiler is 50 kg/s, and the steam parameters are 144 bar and 540°C. In Appendix I is shown the construction of the boiler. Table 2 presents the fuel mixture data.

Table 2. Fuel mixture data

C	52,2 % in d.s.
H	6,1 % in d.s.
N	0,37 % in d.s.
O	38,9 % in d.s.
S	0,03 % in d.s.
Fixed carbon	20,5 % in d.s.
Moisture	53,5 % as received
Volatiles	77,1 % in d.s.
HHV	21,1 MJ/kg in d.s.
LHV	19,8 MJ/kg in d.s.

Values in the Table 2 are calculated from the data of the six samples taken in December 2000. From Table 2 can be noticed the high amount of volatiles in the fuel. It contributes the formation of NO_x, although the nitrogen content of the fuel is low. In the Table 3 is shown the design performance of the CFB boiler including guaranteed emissions.

Table 3 Design performance of the boiler

Flue Gas Exit Temperature	130ºC
Boiler Efficiency	91,6 %
NO_x Emissions	20 mg/MJ
N_2O Emissions	10 mg/MJ
CO Emissions	90 mg/MJ
SO_2 Emissions	50 mg/MJ
NH_3 Emissions	10 ppm
Particulate Matter (dry)	20mg/m^3n

The CFB boiler is equipped with flue gas recirculation. Combustion air is introduced to the boiler as primary air underneath the bed and as secondary air above the bed. Fuel is introduced to the boiler along two fuel feed lines. There is no need to dry the fuel because the boiler is designed to be able to burn the fuels with maximum moisture of 55 %. Flue gases are cleaned with a hybrid SNCR/SCR system and with an electrostatic precipitator (ESP).

4.1.1.2 Nitrogen Oxides Abatement at the Power Plant

The NO_x emission level in the CFB boiler is low because of the optimal circumstances for nitrogen oxide reduction. Combustion temperatures are low, and fuel feed and air delivery are staged. In the CFB boiler, the average furnace temperature is about 850ºC, which is low enough to prevent the formation of the thermal NO_x emission. Flue gas recirculation has a significant effect on the NO_x generation. It seems to inhibit the NO_x formation as it slows down the NO_x reactions in the furnace. It also decreases O_2 concentration in the furnace, which also prevents the NO_x formation. Originally, the flue gas recirculation was introduced as a way to reduce nitrous oxide N_2O, if such a demand would occur, but now it is used to control the bed temperature instead. All these expedients together would be enough to keep the NO_x levels within the emission limits. The emission level of 70 mg/MJ can be reached with the CFB boiler equipped as described above.

In Sweden, the environmental legislation has quantified the price for every kilogramme NO_x emitted from the power plant. Boilers, thermal output of which is more than 10 MW or annual heat production more than 50 GWh, are under the surveillance of authorities. The NO_x emissions of the power plants are compared and the average NO_x emission per produced MWh is defined. Those who are under the average will gain economical profit whereas those who are above the average have to pay the NO_x charge. This has made it possible to use more efficient NO_x abatement methods at the Swedish power plants. At the power plant of Brista Kraft Ab, the NO_x concentration of the flue gas is reduced with SNCR/SCR hybrid method.

Typical wood waste fuel contains about 0,5 w-% nitrogen, which is the main source of NO_x in the CFB boiler. The fuel mix of the Brista Kraft seems to contain little less nitrogen as its nitrogen content is only 0,37 %. The only effective method to reduce the fuel-originated NO_x is to remove it from the flue gases. The hybrid NO_x abatement system is integrated as a part of the CFB boiler. Ammonia-water solution is pumped from ammonia storage tank with a side channel type of centrifugal pump. Rotational speed of the side channel pump is controlled with an inverter. The ammonia feeding equipment includes two ammonia pumps, from which one is in the reserve. In Figure 42 is illustrated the ammonia feeding station of the power plant.

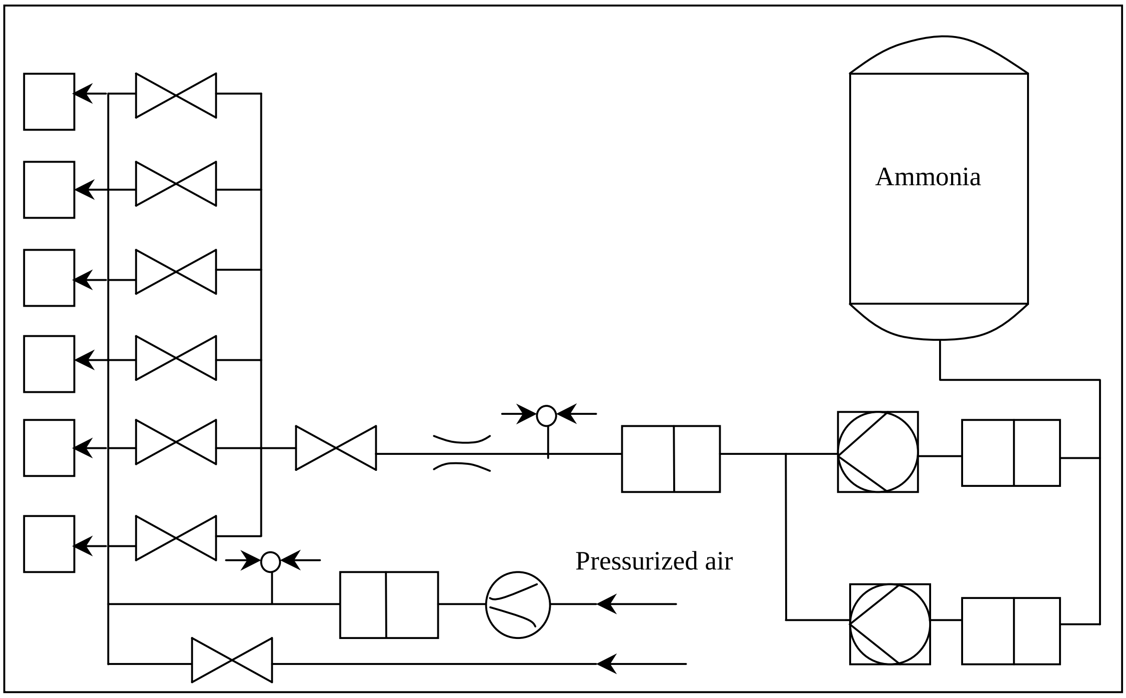


Figure 42. Ammonia feeding station at the power plant

According to SNCR method the 25-% water solution of ammonia is injected to both particle separators of the boiler (see Appendix I). Usually, only two of the four ammonia lines are used simultaneously. The lower left and upper right injection points have mostly been used for ammonia injection. The average particle temperature of the boiler is 760ºC, which is a little bit too low for SNCR method, but in spite of that it seems to be possible to reduce NO_x in such temperatures. The explanation for this is that the measurement of the separator temperature is placed near the separator wall, which is cooler than the other parts of the separator. In general, the temperatures in the separators are sufficient for SNCR reactions. Injecting the ammonia to the separators guarantees adequate mixing with flue gases. To secure the adequate reduction of NO_x in such low temperatures, excess amounts of ammonia must be injected. The NH_3/NO_x -molar ratio of 1,5-2 should be enough to keep the guaranteed emissions although the use of the catalyst allows bigger molar ratios.

The NH_3 emission, which is called also ammonium leakage or slip, is reduced in the catalyst. The catalyst is located in the convective pass of the CFB boiler between two economizer bundles. This location of the catalyst is called high dust location because the flue gas still contains ash as it passes the catalyst. Temperatures around the catalyst are between 300 and 400°C, which is a suitable temperature area for successful SCR and NH_3 reduction. Catalyst is of honeycomb type, and the catalyst material is extruded in the form of square. The catalyst is optimized for bio-fuel combustion, and it is manufactured by Hüls. The total catalyst volume is 32,5 m^3, and its canal size is 6 mm. In Figure 43 is shown the catalyst structure.

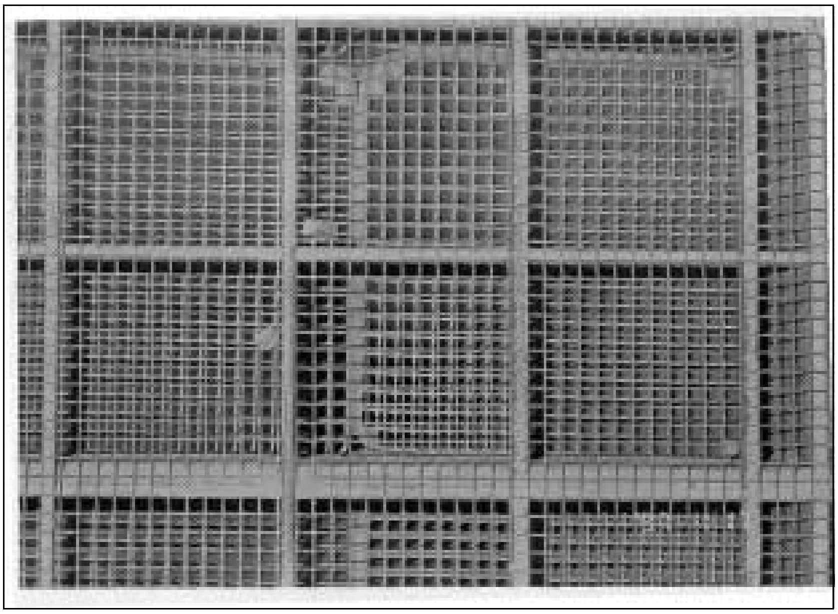


Figure 43. Catalyst structure

The expected amount of operation hours for the catalyst is 16 000 hours. The observed decrease in catalyst activity with similar catalyst in similar conditions has been 15 % after 3400 hours and 20 % after 8800 hours. The latest information is that the activity of the catalyst has decreased to half of the original activity. The ash from wood waste combustion includes 40-60 % alkali and alkaline earth metals, which cause the poisoning of catalyst. This explains the deactivation partly. Another reason can be a short residence time between the final combustion and the catalyst. Significant catalyst blocking and mechanical damages have not been observed so far. Possibilities to regenerate the catalyst have been studied recently. The latest attempt to recover the catalyst has been done with sulfur. The purpose of this test was to sulphatize the alkalis, which decrease the specific surface area of the catalyst by chemical reaction. It seems that the catalyst performance has improved after sulphatizing, but the final results of the sulphatization aren't ready yet.

The overall performance of the hybrid NO_x abatement system has been good. The system tolerates well load changes as the NO_x reduction in SCR increases with lower loads. In the year 2000 the average NO_x emission as NO has been 30 ppm with the average ammonium leakage of 5 ppm. Värmeforsk has studied the performance of the hybrid NO_x abatement system at the power plant. A grid measurement has been made with a DOAS gas analyzer to study the NO_x concentration before the catalyst. According to Värmeforsk study, the SNCR performance can be increased when the NH_3/NO_x -molar ratio is increased. The use of the catalyst allows higher ammonia slip. Table 4 presents the NO_x reduction in the catalyst.

Table 4. NO_x-reduction in the catalyst with different loads and molar ratios (Niemann et al. 2000)

	40 % Load	**70 % Load**	**100 % Load**
NH_3/NO_x = 1,3	2,9 %	8,4 %	13,4 %
NH_3/NO_x = 2,2	63,9 %	47,2 %	65,2 %
NH_3/NO_x = 2,8	76,7 %	64,1 %	60,4 %

Table 4 shows that with the lowest molar ratio, the NO_x reduction takes place before catalyst. With the full load the molar ratio must be lower to avoid too high ammonia slip.

4.1.1.3 Continuous Emission Measurement System of the Power Plant

Power plant of Brista Kraft Ab reports the following emissions to the authorities: CO, NO_x, NH_3, N_2O and particulate matter. CO, NO_x and N_2O are measured from the sample flow of flue gas taken from the duct before the stack. NH_3 is measured in-situ in the stack. Particulate matter is measured directly from the flue gas duct with optical measurement manufactured by Durag. Flue gas sample line leads to the analyzer room equipped by Boo Instrument Ab. O_2, CO and NO are analyzed with a multi-component gas analyzer Multor 610 manufactured by Maihak. It is a NDIR analyzer for continuous emission measuring. O_2 concentration is analyzed in an electrochemical cell. The maximum display delay of Multor 610 is 25 s depending on the cuvette length, gas flow rate and number of components.

N_2O is analyzed with a single-component gas analyzer Unor 610 manufactured by Maihak. It is a precision-NDIR analyzer meant for continuous emission measuring. NH_3 and H_2O are analyzed with laser diode spectrometer LDS 3000, which is based on the absorption of laser diode light with certain wavelength in the measured gas. The response time of the analyzer is less than two seconds. According to the latest calibration measurements in December 2000 all the measuring errors of the analyzers were within the accessible error range. The emission information is collected with Pannlog Win data acquisition program, which will calculate daily, monthly and annual reports about the measured emissions. In Appendix II is shown a schema of the emission measuring system.

4.1.2 Process Control System of the Power Plant

The control actions take place in programmable logic controllers (PLC). Programmable logic controllers include a central processing unit (CPU), power supply unit and some digital or analog input cards and output cards. Setpoint value from the distributed control system (DCS) and measurement from the process are the inputs, which are compared in the CPU. CPU changes the output value if control action is needed. Input signals are transferred as analog signals and converted to digital signals for the processing in CPU. Digital output signal is converted to analog signal after CPU. The DCS of the power plant is Contronic supplied by Hartmann & Braun. Aspen process explorer is used to organize and present information about the power plant process.

The main control of the Bristaverket is realized as boiler following control, which keeps the constant steam pressure and the changes in the load are compensated by changing the firing rate of the CFB boiler. The control concept is presented in Figure 44.

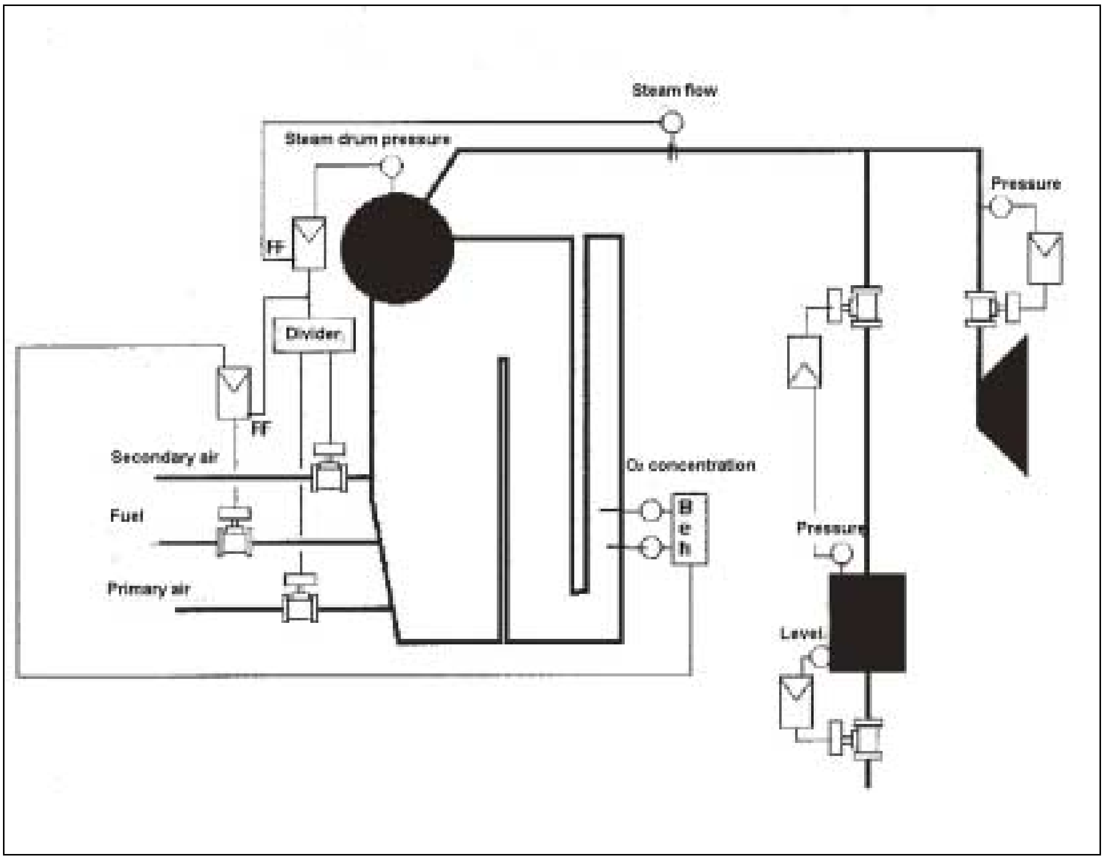


Figure 44. Main control principle of Bristaverket

The main control of the power plant is realized as control of the steam drum pressure. The output of steam drum pressure controller sets the total air amount. The same output signal goes also to fuel feed controller. If the steam flow and the needed load aren't in balance, the steam drum pressure controller changes air distribution and fuel feed simultaneously. The O_2 controller keeps the balance between air distribution and fuel feed correct. Thus, the firing conditions of the furnace are controlled with the main controller, which has a significant effect on the NO_x formation. Especially, optimal air distribution control reduces the NO_x emission of a CFB boiler.

4.1.2.1 Present Ammonia Injection Control at the Power Plant

The ammonia injection pressure is controlled via adjusting the rotational speed of the ammonia pump with an inverter. In the Appendix III is shown the control scheme of ammonia feed. The ammonia feed control is realized with traditional control methods using PI-controllers. Signals from NO_x measurement and ammonia slip measurement are led to a PI-controller, which gives a signal about the ammonia need to a multiplier. A signal from fuel/ammonia proportioning is also led to the multiplier, which in turn gives the ammonia need corrected with the fuel flow. Signal of the ammonia need leaves from the multiplier to another PI controller, which compares the actual ammonia flow and the ammonia need given by the previous PI controller. If there is a difference, the inverter changes the rotational speed of the main ammonia pump. Thus, the outlet pressure of the ammonia pump changes.

Earlier there has been an attempt to control the ammonia flow with a control valve. This control method is no longer in the use because it is uneconomic and the results were not that good. After the ammonia flow measurement and the main ammonia valve, the ammonia line splits into four lines, which lead to the ammonia nozzles. The choice of the lines to be used is made by opening the actual solenoid valves. The inlet pressure of the nozzles is controlled with the ammonia pump. The value of the inlet pressure varies normally between 2,5-4 bar.

3.1.2.2 Performance of the Present Ammonia Injection Control

In Appendix IV are shown the NO_x emission, NH_3 slip and ammonia feed rate of the CFB boiler. From Appendix IV it can be seen that the ammonia feed rate fluctuates constantly. This implies that the ammonia injection control is not stabile. It decreases the ammonia flow too fast causing the oscillations in NO_x and NH_3 emission. Appendix IV shows that the dead time and the time constant of NO_x control can be add up as much as ten minutes. When the ammonia injection is controlled according to the feedback from NO_x measurement, it is not fast enough to prevent NO_x peaks shown in Appendix IV. If a NO_x peak appears, the ammonia injection control increases ammonia feed rate so slowly that peak is already over when ammonia starts to affect. This causes high ammonia slip and increases ammonia consumption unnecessarily. Thus, it seems that some other control method would be a better option in this case.

4.2 Ammonia Feeding Equipment

New ammonia feeding equipment includes an ammonia pump and two solenoid valves for each ammonia feed line. Furthermore, it includes a new PLC in the cross coupling, and a local control display in a laptop computer for the control of ammonia feeding equipment. Process data is stored in the laptop, which displays process values on-line, and it can also be used in exploring the data. The laptop is equipped with remote control possibility.

4.2.1 Description of the Ammonia Feeding Equipment

In the development of new ammonia feeding equipment, two main ideas are that ammonia can be injected to different feeding points at the both separators, and the amounts of the injected ammonia can be controlled individually at each of the feeding points. In Appendix V are presented the locations of ammonia feeding points in separators. Need for the use of different ammonia feeding points may occur if the boiler load changes, or if the combustion process is unbalanced. As the boiler load changes, the temperatures in the particle separators change as well. For reaching the optimal SNCR performance with higher loads, it may be necessary to inject more ammonia to the higher injection points. The unbalance of the combustion process can be detected from the difference in the O_2 values on the right and left side of the CFB boiler. In the case of the unbalance it may be necessary to inject more ammonia to the side which has the higher O_2 amount. This action is based on a fact that the in the presence of extra O_2, more NO_x is formed. Thus, the NO_x concentration can vary on the different sides of the boiler, and some extra ammonia may be needed locally.

New ammonia pumps and their solenoid valves are installed in parallel with old solenoid valves in the each of the ammonia lines In the Figure 45 are shown an ammonia pump and solenoid valves as well as ammonia feed lines for the lower right ammonia injection point.

Figure 45. *Ammonia feeding equipment*

Ammonia pumps are piston-membrane pumps manufactured by SER. The maximum capacity of one ammonia pump is 108 l/h, and it produces a pulsatile flow. The outlet pressures of the pumps are controlled by changing the length of the piston stroke. The inlet pressure of ammonia pumps is fixed with the outlet pressure of the main ammonia pump.

Local control display for the ammonia feeding equipment is created with InTouch –software by Wonderware and configured to the laptop in the control room. It includes a PI scheme of the ammonia feeding equipment, as well as some trends and alarms. In Appendix VI is shown the PI scheme of the ammonia feeding equipment. The PI scheme displays process values and includes pop-up control windows for ammonia pumps and solenoid valves. Their control can be either automatic, so that the controller performs the control actions or manual, so that the operator performs the control actions. The local control display is only a temporarily solution, which is configured for the tests. In practice, the user interface of the controllers is the DCS of the power plant.

4.2.2 Description of the Data Acquisition

20 different process values are collected continuously with the laptop of the local control display. Data acquisition takes place every ten seconds. In Table 5 are shown the observed process values.

Table 5. Observed process values

Identification no.	Measurment	Scale
LBA20CF201	Load (steam flow)	0-60 kg/s
HBK11CP902	Bed pressure	0-12 kPa
HBK11CT901	Bed temperature[1)]	0-1200ºC
HBK11CT206	Furnace temperature[1)]	0-1200ºC
HBK20CT201	Cyclone temperature[1)]	0-1200ºC
HBK20CQ201	O_2 left side	0-20 %
HBK20CQ201	O_2 right side	0-20 %
HLA10CF201	Primary air	0-40 Nm^3/s
HLA20CF201	Secondary air	0-40 Nm^3/s
HNF10CF201	Recirculation gas, left	0-7 Nm^3/s
HNF10CF202	Recirculation gas, right	0-7 Nm^3/s
HNA30CQ201	NO_x	0-500 mg/Nm^3
HNA30CQ202	CO	0-2000 ppm
HNA30CQ204	NH_3	0-100 %
HNA30CQ207	Moisture in flue gas	0-40 %
HSK30CF201	Ammonia flow	0-6 kg/min
aoPump_P001	Ammonia pump high left	0-100 %
aoPump_P002	Ammonia pump low left	0-100 %
aoPump_P003	Ammonia pump low right	0-100 %
aoPump_P004	Ammonia pump high right	0-100 %

1) calculated average value

The ammonia slip as percents can be converted to parts per millions with the following factor: 25 % is equivalent to 10 ppm. Process values are transferred from the logic as analog signals to the Omron host link, which converts them into bytes. The process values are stored at the laptop in binary form and in Microsoft's Access format. The process data can be transferred from the laptop via GSM card modem. PcAnywhere software by Symantech is used for the data transformation. The GSM card modem can be used also in remote controlling of ammonia feeding equipment. Due to the remote controlling possibility it isn't always necessary to travel to Sweden or bother the operators when process data needs to be transferred or process to be observed.

4.3 Testing Procedure

Performance of the new ammonia feeding equipment was tested at the power plant. NO_x, O_2 and CO concentrations were measured from the convective pass before the catalyst during the tests. The aim was to collect information about the correlations between the NO_x emission and observed process values, and about the ammonia need of the hybrid NO_x abatement system. The new ammonia feeding equipment was in the use at the first time during the test period.

4.3.1 Ammonia Feeding Test Runs

Three different load cases were defined for the tests: 50 %, 75 % and 100 % of the maximum load. In the Appendix VII is shown the complete test plan. Tests were done between 11. and 20. December 2000. One test was carried out for about two hours. New ammonia pumps were used in different combinations to vary the ammonia feed in different feeding points (see Appendix V). Load case 100 % is equivalent to 122 MW_{th}, load case 75 % is equivalent to 91,5 MW_{th} and load case 50 % is equivalent to 61 MW_{th}. The allowed load variation during the tests was ±5 kg/s. One test with each load was done completely without ammonia injection to find out the base level of NO_x emission at different loads. A special test was performed to optimize ammonia injection manually by feeding different ammonia amounts to the different feeding points. The aim was to find the balance between NO_x emission and ammonia slip. The effect flue gas recirculation on NO_x emission was studied during this test. This was realized by keeping the flue gas recirculation flow constant.

Because the test equipment was in the use for the first time, some problems occurred. There were a few leaks in the new ammonia lines and at least one ammonia nozzle was completely blocked. For example: tests were begun with two lines, but soon it became evident that only one line lets ammonia through. Joint parts were tightened and the blocked nozzle was opened. No leaks in the ammonia lines were allowed because ammonia is a harmful substance. The inlet pressure of the new ammonia pumps was difficult to adjust because it depends on the actual rotational speed of the main ammonia pump. With too high inlet pressures, the piston pumps let all the ammonia through, and the feed rate could not be controlled. With too low inlet pressures, no ammonia at all came through, or the pumps had to be used near their maximum capacity, which may cause problems in the long run. In addition to this, the performance of the ammonia pumps depends on the ammonia flow, which in turn is linked to the boiler load. Thus, the optimal rotational speed of the main ammonia pump is between 50-55 % of the maximum speed 1800 rpm and the optimal inlet pressure of the piston pumps is between 1-2 bar.

Suitable weather conditions were essential for the successful test period. Because the weather was colder than it was thought, it was not possible to perform all the tests with 50 % load. The reason for this is that the district heating consumption increases when the outdoor temperature decreases. One pulverized wood-fired boiler, a couple of oil-fired boilers and heat pumps are in the same district heating network with Bristaverket. Oil fired boilers were in use during some low load tests. At the second week of the test period, the weather was clearly colder. The pulverized wood-fired boiler was not in use, which also made it impossible to perform the rest of the tests with 50 % load. The tests without the ammonia injection were the most important tests because it is possible to calculate the theoretical ammonia need with the results from these tests. They were carried out only for an hour because of the higher NO_x -emissions. The NO_x -emission limit 70 mg/MJ was temporarily exceeded during the tests but mostly the emissions remained under the limit. Short time exceedings of the emission limit don’t have a significant effect on the annual NO_x -emission, which is observed by the authorities.

4.3.2 Measuring of Emissions

Following emissions were measured from the convective pass before the catalyst: NO_x, CO and O_2. Emissions were measured during the whole test period. Measuring was suspended only during the calibrations of the analyzers. Emissions were measured by using four measuring joints at the boiler wall. Net measurement was not considered necessary because Värmeforsk had already done it earlier.

4.3.2.1 Measuring Equipment

Measuring equipment included following components:

1. 2 EPM Diluting Stack Samplers
2. 2 Monitor Labs Inc. Nitrogen oxides analyzers
3. 2 Servomex O_2 analyzers
4. Hartmann & Braun Uras 10 E CO analyzer
5. Thermo Environmental Instruments Inc GasFilter Correlation CO analyzer
6. 2 pumps for the NO_x analyzers
7. Diluting air dryer
8. Sample dryer
9. 2 silica gel bottles
10. Pump for the sample dryer
11. Agilent 34970A Data Acquisition/Switch Unit
12. Gas container CO 209 ppm and synthetic air
13. Gas container N_2 99,999 %
14. Gas container NO_2 100 ppm, NO_x 103 ppm and N_2

In the Figure 46 is shown the measuring equipment.

Figure 46. Measuring equipment

The measuring point 3 for the NO_x can be found from the Figure 46. NO_x was measured from points 2 and 3 in the middle. O_2 and CO were measured together from the measuring points 1 and 4 at left and right sides respectively. Analyzers were calibrated almost every morning.

The NO_x probe included critical orifice for the sample diluting. The sample was diluted because the measuring range of the analyzer is 0-1 ppm, and the NO_x -concentrations in the flue gases are significantly higher than that. The probe capacity was 100 ml/min. The sample was collected with diluting stack sampler unit and it was analyzed from the moist gas with an analyzer based on chemiluminescence. Similar equipment was used for both NO_x -measurements. Zero calibration of the NO_x -analyzers was performed with calibration gas N_2. Span calibration of the NO_x analyzers was performed with calibration gas, which included 103 ppm NO_x in N_2. In Appendix VIII are shown the typical calibration curves. From Appendix VIII can be seen that the left NO_x -measurement rises very slowly in the span calibration. The rise time of the left NO_x -measurement was about 17 minutes as the rise time of the right NO_x -measurement was about 3 minutes. According to the manual of the analyzer, 3 minutes is the normal value for the rise time. Thus, the measuring time must be long enough to ensure the reliable measuring results.

O_2 and CO concentrations were measured from a common sample. Sample was sucked through the probe to the sample dryer. Thus, the components were measured from the dry gas. O_2 was analyzed with an analyzer based on paramagnetic susceptibility of O_2. The zero calibration of O_2 analyzer was performed with calibration gas N_2. The span calibration was performed with air, which includes normally 20,9 % O_2. CO was analyzed with an analyzer based on NDIR. The zero calibration of the CO analyzers was performed with calibration gas N_2. The span calibration of CO analyzers was performed with calibration gas, which included 209 ppm CO in the synthetic air.

4.3.2.2 Emission Measurement Data Acquisition

Measuring data from the analyzers was collected with Agilent 34970A data logger. In the Table 6 are shown the data acquisition parameters.

Table 6. Data acquisition parameters

Channel	Name	Signal	Range
01	O_2 left	0-0,25 V	0-25 %
02	O_2 right	0-0,25 V	0-25 %
03	NO_x right	0-5 V	0-200 ppm
04	NO_x left	0-5 V	0-200 ppm
05	CO right	0-1 V	0-100 ppm
06	CO left	0-5 V	0-500 ppm

Scan interval during the tests was ten seconds. Scan interval of one second was used for some calibrations. Data acquisition program was Agilent Benchlink. The measuring data was stored in a laptop computer. Scanning was stopped during the test period only to change the scan interval between one and ten seconds. The emission measurement data can be exported to a spreadsheet program as comma separated values.

4.4 Results

The theoretical ammonia need for the NO_x abatement and the possible correlations between the NO_x -emission and the observed process values (see Table 5.) were gathered as the results from the ammonia feeding tests. The most important results are the parameters, which can be used in construction of a new controller. This includes the results mentioned above and additionally the averages and the standard deviations of the process values, which are correlating with the NO_x emission or which predict the formation of a NO_x peak.

4.4.1 Process Data Analysis

The collecting of the process data began 17.10.2000, and the steam production started after the annual summer outage 27.10.2000. Process data can be considered representative. Boiler load has varied greatly due to the fluctuation of the district heating need. In the Table 7 are shown the averages of the process values with their standard deviations.

Table 7. Averages and standard deviations of the process values

Measurement	**Average**	**Standard deviation**
Load (steam flow)	40 kg/s	9 kg/s
Bed pressure	3,6 kPa	0,8 kPa
Bed temperature[1)]	840 ºC	34 ºC
Furnace temperature[1)]	850 ºC	30 ºC
Cyclone temperature[1)]	760 ºC	53 ºC
O_2 left side	3,3 %	1,5 %
O_2 right side	3,5 %	1,4 %
Primary air	32 Nm^3/s	3,3 Nm^3/s
Secondary air	22 Nm^3/s	6,0 Nm^3/s
Recirculation gas, left	1,5 Nm^3/s	0,8 Nm^3/s
Recirculation gas, right	1,4 Nm^3/s	0,8 Nm^3/s
NO_x	67 mg/Nm^3	35 mg/Nm^3
CO	60 ppm	68 ppm
NH_3	14 %	6,4 %
Moisture in flue gas	8,2 %	1,9 %
Ammonia flow	1,4 kg/min	0,5 kg/min

The averages are calculated from the data gathered between 27.10.2000 and 23.2.2001. Data during any shutdowns is left outside the study. The averages are calculated from the hourly averages, which are generated from the binary data taken every ten seconds. The converted average NH_3 slip is 5,5 ppm and the standard deviation is 2,6 ppm with the assumption that the conversion factor behaves linearly. The average NO_x emission is about 22 mg/MJ which is only 32 % of the emission limit.

It is possible to evaluate the ammonia need of the NO_x -abatement system with the help of the collected data. An approximation for the flue gas flow rate is needed for the evaluations. It is not included in the observed process values, but it can be calculated from the process data. First, we define the stoichiometric air coefficient of the combustion

$$\lambda = \frac{21}{21 - O_{2,meas}} . \tag{17}$$

Then, we define the theoretical air amount $q_{v,a(theor)}$ with the help of primary and secondary air flows $q_{v,a,prim}$ and $q_{v,a,sec}$

$$q_{v,a(theor)} = \frac{q_{v,a,prim} + q_{v,a,\sec}}{\lambda} . \tag{18}$$

For every fuel, the theoretical relation of the flue gas flow $q_{v,fg(theor)}$ and air flow $q_{v,a(theor)}$

$$\frac{q_{v,fg(theor)}}{q_{v,a(theor)}} \approx 1 . \tag{19}$$

The moisture φ in the flue gas is defined with the water content of flue gas $q_{v,H2O}$

$$\varphi = \frac{q_{v,H_2O}}{q_{v,fg}} . \tag{20}$$

Thus the flue gas flow $q_{v,fg}$ can be defined

$$q_{v,fg} = q_{v,fg(theor)} + q_{v,H_2O} . \tag{21}$$

From Equations (20)-(21) can be solved

$$q_{v,fg} = \frac{q_{v,fg(theoretical)}}{(1 - \varphi)} . \tag{22}$$

From the Equations (17)-(19) can be solved

$$q_{v,fg(theor)} = \frac{\left(q_{v,a,prim} + q_{v,a,\sec}\right)\cdot\left(21 - O_{2,meas}\right)}{21}. \tag{23}$$

The final equation for the approximation of the flue gas flow is as follows

$$q_{v,fg} = \frac{\left(q_{v,a,prim} + q_{v,a,\sec}\right)\cdot\left(21 - O_{2,meas}\right)}{21\cdot\left(1-\varphi\right)}. \tag{24}$$

Thus, the average flue gas flow is approximately 42 Nm^3/s and the standard deviation is 8,6 Nm^3/s. With the Equation (8) of the SNCR reaction, it is possible to evaluate the ammonia need of the NO_x abatement system.

$$\frac{n_{NH_3}}{n_{NO_x}} = \frac{\dfrac{m_{NH_3}}{M_{NH_3}}}{\dfrac{m_{NO_x}}{M_{NO_x}}} = \frac{4}{1}, \tag{25}$$

where n is reaction order, m is mass and M is molar mass. First, we have to convert the ammonia flow and NO_x -emission to the unit [mol/s]. It can be done when we know the molar weights of the NO_x and NH_3. Estimated value for the molar weight of the NO_x is 46 g/mol. This comes from the assumption that eventually all the NO will form NO_2. The ammonia flow is converted to the [mol/s] as follows:

$$\dot{n}_{NH_3} = \frac{\dot{m}_{NH_3}}{4\cdot 17\dfrac{g}{mol}\cdot 60\dfrac{s}{\min}}\cdot 1000\frac{g}{kg}. \tag{26}$$

The NO_x emission is converted to [mol/s] as follows:

$$\dot{n}_{NO_x} = \frac{c_{NO_X} \cdot \dot{m}_{fg}}{1000\frac{mg}{g} \cdot 46\frac{g}{mol}} \quad , \tag{27}$$

where c_{NOx} is NO_x concentration in the flue gas. The ammonia need is

$$\dot{n}_{NH_3,need} = \dot{n}_{NH_3} + \dot{n}_{NO_x} \; . \tag{28}$$

Finally we have the calculated ammonia need of 0,4 mol/s. This has to be converted back to the unit [kg/min] as follows

$$\dot{m}_{NH_3,need} = 4 \cdot \frac{\dot{n}_{NH_3,need}}{1000\frac{g}{kg}} \cdot 17\frac{g}{mol} 60\frac{s}{\min} \; . \tag{29}$$

Thus, we attain the average ammonia need of 1,7 kg/s with the standard deviation of 0,4 kg/s.

There are certain correlations, which can be found straight from the collected data. From Appendix IX it can be seen that the CO emission is in the opposite phase compared to the NO_x emission. If the CO concentration is high, it has a deoxidizing effect, and the NO_x concentration will be reduced. On the other hand, the SNCR reaction may produce more CO, which means that the interactions between CO and NO_x are not as simple as could be thought. According to theory, an increase in O_2 concentration of the flue gas should exhibit the increase of the NO_x –concentration as well. In Appendix X is shown an example about this. This results from the fact that in the presence of extra oxygen in the furnace, more NO_x will be formed. Another correlation can be found between the flue gas recirculation and the NO_x emission. In Appendix XI is shown an example about this. If the bed temperature of the boiler is high, the flue gas recirculation rate is increased, and the O_2 concentration in the furnace will be reduced. Inert cold gas will also slow down the chemical reactions and there will be less NO_x.

The boiler load is evidently the most significant factor in the formation of NO_x. In Appendix XII is shown an example about this. It seems that the firing rate has a great effect on NO_x emission, and for example changes of O_2 -concentration in the flue gas result from changes of the firing rate. Thus, it can be concluded that the boiler unbalance, which means that firing rate is smaller on the one side of the boiler than on the other, would produce different NO_x -concentrations on the different sides of the boiler. This duality results from the fuel feed, in which two lines supply fuel to right and to the left side of the boiler. These assumptions can be studied by considering the results of the emission measurements

4.4.2 Emission Measurement Data Analysis

The averages and standard deviations for measured emissions can be presented as results from the emission measurements. They are shown in Appendix XIII. From the results, it can clearly be seen when the ammonia has been injected to one side only. When it has been injected to both sides, it seems that on the right side of the boiler the reducing effect is better than on the left side. One reason for this could be a partial blockage of a nozzle on the right side. It can be seen from the CO values that the uneven fuel feed to the different sides of the boiler causes unbalance. At the right side of the boiler, appears to be more CO than at the left side. Here, it must be reminded that the right and the left side are defined by standing in front of the boiler where the cyclone separators are. Emission measurement points, which are located at the convective pass, are defined as mirror image to this. In the Appendix XIV are shown the reduced emission measurement results. They are converted to the O_2 concentration of 6 %. Current loads are compared to the test load cases, which are 25 kg/s, 37,5 kg/s and 50 kg/s and the ammonia feed is compared to 1 kg/s as follows:

$$c_{NO_x,red} = \frac{21\% - 6\%}{21\% - O_{2,meas}} \cdot \frac{\dot{m}_{steam}}{25\frac{kg}{s}} \cdot \frac{\dot{m}_{NH_3}}{1\frac{kg}{\min}} \cdot c_{NO_x}. \qquad (30)$$

As it can be seen from Appendixes XIII and XIV, the results have some differences. In the case of one pump used, the reduced emission is significantly greater because the mass flow of the ammonia is closer to 0,5 kg/min than 1 kg/min.

The theoretical value of the ammonia need can be calculated from the emission measurement results. Ammonia need is calculated from the values, which were measured during the tests without ammonia injection. First, the NO_x -values are converted from the unit [ppm] to [mg/Nm^3] as follows:

$$c_{NO_x}\left[\frac{mg}{Nm^3}\right] = c_{NO_x}[ppm] \cdot \frac{M_{NO_x}}{V_{mNO_x}} \quad , \qquad (31)$$

where V_m is molar volume. This result has to be converted to the unit [g/s] as follows:

$$\dot{m}_{NO_x} = c_{NO_x} \cdot \dot{m}_{fg}. \qquad (32)$$

With the assumption that the molar ratio of ammonia and NO_x is one and the NO_x reduction without ammonia injection is zero, the ammonia need for NO_x reduction can be calculated as follows:

$$m_{NH_3} = \frac{m_{NO_x}}{M_{NO_x}} \cdot M_{NH_3}. \qquad (33)$$

Finally, the result must be converted to [kg/min] and calculated as water solution including 25 w-% ammonia as follows:

$$m_{NH_3} = \frac{60\frac{s}{\min}}{1000\frac{g}{kg}} \cdot \frac{m_{NH_3}}{0{,}25}. \tag{34}$$

The results for the three load cases of 50 %, 75 % and 100 % are presented in Table 8 as averages with the standard deviations.

Table 8. Theoretical ammonia need according to emission measurements

	Average [kg/min]	**Standard deviation [kg/min]**
100 % right side	1,29	0,06
100 % left side	1,27	0,05
75 % right side	0,82	0,06
75 % left side	0,84	0,05
50 % right side	0,75	0,04
50 % left side	0,76	0,03

These results give the base level of ammonia need in different load cases. They are ideal because of the molar ratio assumption. In practice, the molar ratio is more than one depending on the temperature window at the ammonia injection points.

In Appendixes XV-XVII are shown the figures of the process values, which seem to correlate with the NO_x -emission. Load has the strongest correlation to NO_x -emission and its effect can be seen also in the primary and secondary air, as well as in the separator temperature. The correlation between O_2 and NO_x emission cannot be seen from the figure because O_2 is not a free parameter. The same applies between flue gas recirculation and NO_x emission. Nevertheless, they can be used in the controller configuration because their changes seem to indicate a change in the NO_x emission. The effect of CO can be clearly seen from the figure, but in the configuration of the controller this information is useless because the reducing effect of CO is present only if the CO concentration is higher than normally.

4.4.3 Ammonia Feeding Test Results

The ammonia feeding equipment was tested at the first time, and its overall performance was good, although some modifications can be recommended. One of the biggest problems was to produce the needed ammonia flow with the new ammonia pumps. Their inlet pressure was difficult to adjust so that the new pumps performed uniformly in all conditions. It is possible to produce so high inlet pressure with the main ammonia pump that it might be possible to replace the new ammonia pumps with control valves. The performance of the ammonia flow measurement is questionable, especially with the smaller flow rates as the measurement works after the Coriolis principle. Nozzles seem to block easily unless they are not in constant use. The new ammonia pumps create a pulsating flow, which can damage the flexible ammonia tubes in the course of time.

During the tests, it became evident that the upper ammonia feeding points are the most useful ones. Especially with the higher loads, it was better to inject more ammonia to the upper feeding points than to inject it to all feeding points. This was proven during the test period when ammonia flow rate was controlled manually. The boiler was operated with the maximum load. Ammonia injection to the lower injection points seemed to increase the ammonia slip. Flue gas recirculation flow was set to constant and it seemed to even up the NO_x -emission but it did not eliminate the periodic fluctuation of the NO_x emission. The test did not cause disturbances to the bed temperature, which is controlled with flue gas recirculation. Thus, the flue gas recirculation flow can be kept constant when the load is steady.

5. ADAPTIVE CONTROLLER

This work has presented the information needed for the development of an adaptive controller. There are a few options to build the controller for ammonia feeding equipment. The aim is to build an adaptive, robust feedforward controller which will be fast enough to cut down the NO_x peaks. Long time stability of the controller is also required. The reliability of the controller is important because it must function properly without disturbing the power plant process itself.

5.1 Configuration of the Adaptive Controller

The first version of the controller was configurated with the InTouch software by Wonderware. In Appendix XVIII is presented the basic idea of the ammonia injection controller. Fuzzy logic was chosen as control method because it is the most useful method in the case of a few inputs with complex and nonlinear interactions. Fuzzy logic is fast and easy way to build a controller without a traditional model including a transfer function and the dead time. This leaves out the dead time compensation with a Smith predictor. Fuzzy logic is also handy when it comes to building a one-sided proportional control. This means that the control action will be taken only if the change goes to a certain direction. If it goes to the other direction nothing happens. Boiler load, difference between the measured slip and the slip setpoint and following delta values: O_2, separator temperature and recirculating flue gas flow were chosen as input values of the controller. NO_x is also included into the inputs, but at the moment it is disabled because the feedback from the emission measurement is way too slow. Output value is ammonia mass flow as [kg/min]. Load defines the base level of ammonia need. Delta values and the difference between the NH_3 slip and the slip setpoint are used to correct the base level. In addition to this, there are two extra corrections from boiler unbalance and from a change in the optimal injection height. These corrections are called respectively unbalance and level correction.

5.1.1 Fuzzy Controller

The first version of the fuzzy controller was realized with the FuzzyTech software. In Figure 47 is shown the principle of the fuzzy controller.

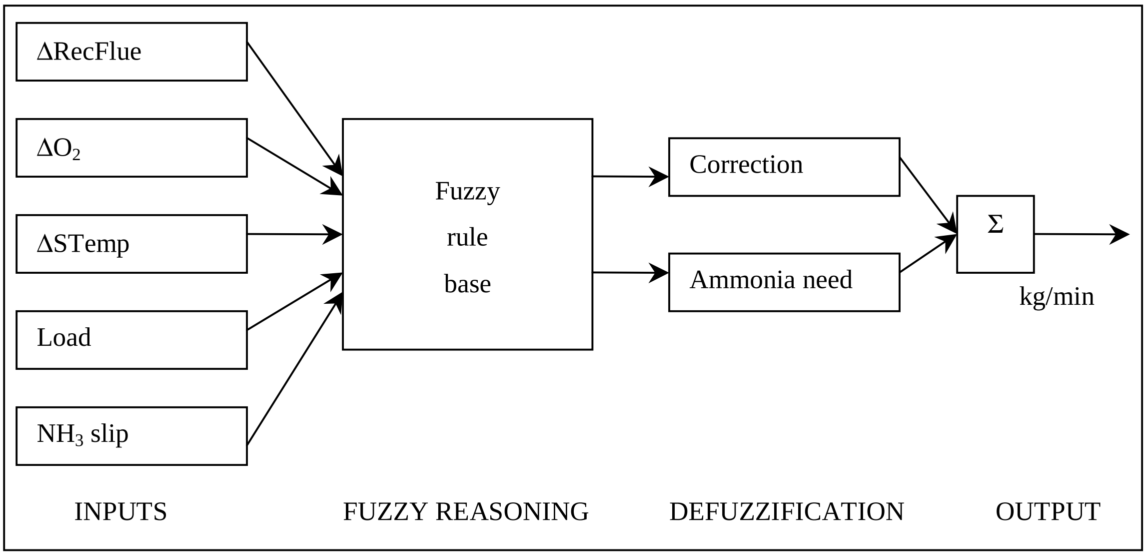


Figure 47. Principle of fuzzy controller

From the Figure 47 can be identified the different phases of the fuzzy control. These phases are fuzzification, fuzzy reasoning and defuzzification. Fuzzification is done with the membership functions, which are defined for each of the inputs. In Figure 48 are shown the membership functions for the separator temperature difference.

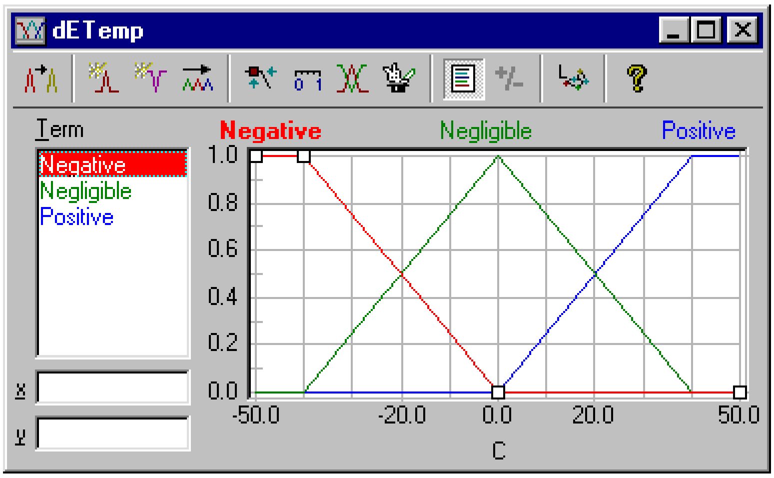


Figure 48. Membership functions of the separator temperature difference

From the Figure 48 it can be seen that a temperature change in the separator can be negative, negligible or positive. For example the membership degrees of the delta value -20ºC are 0,5 in the fuzzy set ’negative’ and 0,5 in the fuzzy set ’negligible’. In the Table 9 is shown an example about the fuzzy rulebase.

Table 9. Fuzzy rulebase

Spreadsheet Rule Editor - RB1

#	IF dETemp	dO2	dRecFlue	Last	NOx	THEN DoS	Correction	THEN DoS	NH3
1				low	low			1.00	Verylow
2				low	medium			1.00	Low
3				low	high			1.00	High
4				medium	low			1.00	Medium
5				medium	medium			1.00	Medium
6				medium	high			1.00	High
7				high	low			1.00	Medium
8				high	medium			1.00	High
9				high	high			1.00	Veryhigh
10	Negligible					1.00	NoAction		
11		Negligible				1.00	NoAction		
12			Negligible			1.00	NoAction		
13	Negative					1.00	Decrease		
14	Positive					1.00	Increase		
15		Negative				1.00	NoAction		
16		Positive				1.00	Increase		
17			Negative			1.00	NoAction		
18			Positive			1.00	Increase		
19									
20									
21									

This rulebase is not the final rulebase as one input is missing, but it presents the principle of the one-sided proportional control as for example only positive change in the temperature diffrence of the cyclone separator results the control action. The fuzzy reasoning is perfomed according to the fuzzy rulebase. Fuzzy rulebase is built using IF…THEN-rules. Rules tell to which direction the controller must react with certain values of the inputs. For example if the load is low and the NO_x emission is high, then the ammonia flow rate must be high. The expression ’high ammonia flow rate’ can be determined as [kg/min] with its membership functions. Because the result of the fuzzy reasoning is not unambiguous, it must be defuzzified. Defuzzification is done with the mass centroid method, which returns the center of area under a membership curve. In Figure 49 is presented the principle of mass centroid method.

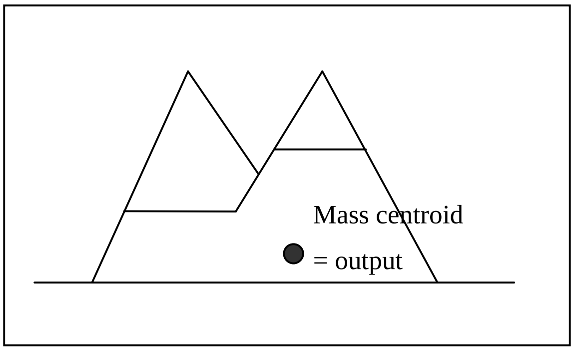


Figure 49. Mass centroid method

5.1.2 Moving Average and Adaptivity

Moving average is used in the calculation of the delta values and the ammonia slip setpoint. The moving average is easier to build than derivative. Moving average is calculated as follows:

$$x'_{n+1} = \frac{n \cdot x'_n + x_{n+1}}{n+1}, \qquad (35)$$

where n is the length of the averaging period, x' is the moving average and x is the measured value. Delta values are calculated as follows:

$$\Delta x = x_{n+1} - x'_n, \qquad (36)$$

where Δx is delta value. Delta values are more informative than the derivatives because they differ from zero as long as the moving average reaches the value of the measurement. Derivatives show only the change and return fast back to zero. The differences between derivative and delta value are shown in the Figure 50.

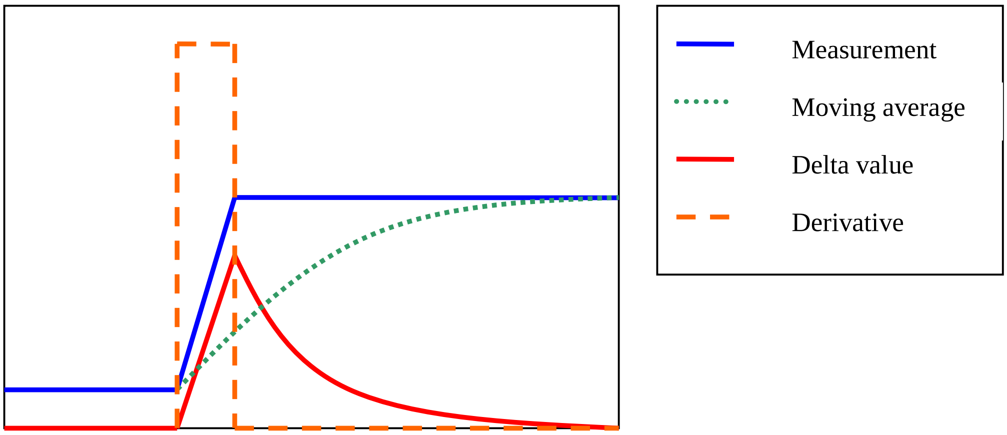


Figure 50. Differences between delta value and derivative

The feature that makes the controller adaptive is the slow integration of the ammonia slip setpoint. The slip set point keeps the ammonia slip below the emission limits, but it also assures that the adequate amount of ammonia will be injected. The set point integration is done on the basis of long time NO_x emission average. If the emission average is high the slip setpoint is increased and otherwise decreased. The integration time of the slip set point is 5 seconds. The set point will increase 0,01 units or decrease 0,005 units during five seconds, depending on the difference between setpoint and measurement.

5.1.3 Ammonia Slip Predictor

A small neural net was configured to predict the ammonia slip. It takes five previous values of the ammonia slip and extrapolates two following values. This means that it predicts 20 seconds forwards, which will help to compensate the dead time of the ammonia slip measurement. In Figure 51, is shown the structure of the neural net.

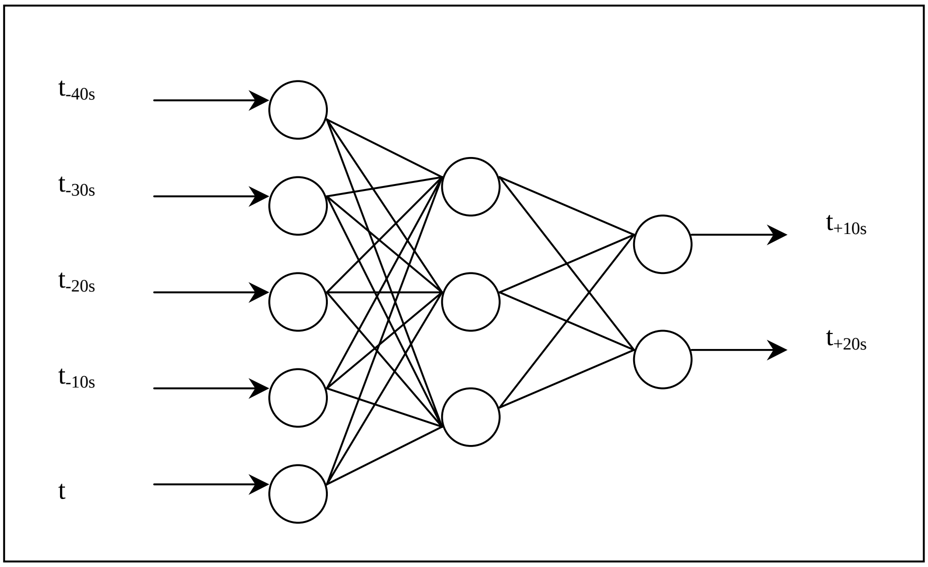


Figure 51. Structure of the neural net

This type of the neural net structure is called multilayer perceptron, which has one hidden layer of neurons. The neural net is taught by using process data from 24 h period. The process data period has been chosen so that the data is presentative.

5.1.4 Unbalance and Level Corrections

Unbalance correction and level correction take control action after the fuzzy controller. Boiler unbalance is corrected according to difference between the right and the left O_2 value. Level correction changes the centroid of ammonia injection so that in case of higher load, more ammonia can be injected to upper injection points. The corrections are realized as proportional control. They are used in correcting the ammonia flow given by the fuzzy controller. These corrections define how the ammonia need is divided between the four ammonia pumps, but they don’t change the total ammonia flow. Thus, the ammonia injection is directed according to possible boiler unbalance and load changes to the ammonia feeding points where it is most needed. The final outputs are control signals for the piston pumps as set point for the positioner converted to 4…20 mA.

5.1.5 Cost Optimization

The cost optimization has been planned to become a part of the adaptive controller, but it has not been configurated yet. The idea is that the one kilogramme NO_x has its price, as well as one kilogramme ammonia. The price of the ammonia slip can be evaluated using the price of ammonia. The ammonia slip costs at least two times the price of the ammonia because the ammonia slip degrades the catalyst. The following equation can be used in the cost optimization:

$$\$ = A_{NO_x} \cdot \dot{m}_{NO_x} + B_{NO_x} \cdot \dot{m}_{NH_3} + C_{NO_x} \cdot \dot{m}_{slip}\,, \qquad (37)$$

where A, B and C are the prices in [SEK/kg]. The prices are multiplied with the respective amounts of NO_x, ammonia and ammonia slip in [kg/h]. The results of the cost optimization can be used in the definition of the slip set point. The optimization could be realized as adaptive so that the minimum of the Equation (37) would be sought continuously, and if it is not reached, the set point of the ammonia slip is changed.

5.2 Installation of the Adaptive Controller

It was fast and easy to install the controller to the local control display of the ammonia injection, because the controller configuration was done in advance. Fuzzy controller was added as module to the InTouch. The controller receives same process values as the local control display. The input values for the controller can either directly be found or calculated from these values. During the time when the first version of the controller was tested and tuned the second version of the controller was programmed to Omron logic. This was done because the computers are less reliable than a PLC. Own user interface for ammonia injection controller is a only a contemporary solution. The user interface must become a part of the power plant's DCS before the controller is taken to full use. The operators must be able to start and shut down the controller, and the alarms from the system must come straight to the operator.

Omron has certain limitations in the programming language. This means that the code of the controller must be as simple as possible. Omron can process only PCD or hexadecimal numbers. Real numbers with lots of decimals must be avoided because they cause errors to the calculation. Only basic calculations like addition, subtraction, multiplication and division can be done. In addition to this, there are some funtions like square root and sin(x) available. For example, involution with real numbers cannot be done in the Omron logic. The performances of the first controller configuration and the PLC must be compared to ensure that the code programmed to the Omron PLC is correct as the programming language used in Omron PLC is quite a different than the simple programming language used in InTouch. This means that the codes can not be compared directly to each other.

5.3 Performance of the Adaptive Controller

The performance of the controller was tested right after the installation and later in the frames of the trial run. The first test was performed to find out if the controller functions as it should, and to tune its performance in the real power plant conditions. Trial run was taken through to demonstrate the better performance of the adaptive controller compared to the old control method. Better performance can be defined as controllers ability to decrease the NO_x emission, to decrease the deviation of the NO_x emission and to produce a steady ammonia flow. Controller must be stabile in the long run, and the robust performance is desirable. During the tests, only higher level pumps 1 and 3 were used because the blocked nozzle in the ammonia line 2 was disturbing strongly the ammonia distribution. The inlet pressure of the piston pumps was fixed by keeping the rotational speed of the main ammonia pump constant.

5.3.1 Tuning of the Controller

During the tuning, it was tested if the controller works as planned. Among the things that were checked were the response, stability and robustness of the controller. The fuzzy rule base was tested in the power plant conditions and some modifications were done. Also the shapes of the membership functions were modified. The time constants of the controller response were tuned by trial-and-error method. They were tuned so that in the case of a NO_x –peak, ammonia is added fast, but the ammonia flow will not be reduced right after the peak is gone. Thus, the ammonia flow remains at the same level long enough to cut down the NO_x -peak and the flow will be more stabile. The need for this action was observed in the step response test when the boiler load was changed stepwise. The step response of the controller can be seen in Appendix XIX. It can be seen that addition in the ammonia flow and the NO_x -emission peak have occurred at the same time. Ammonia has cut down the NO_x –peak and NH_3 slip has increased about two minutes later. The NH_3 peak has been so high that the measuring range of the analysator was exceeded.

During the tuning, it became evident that the controller must identify which pumps are in the use, so that it can divide the ammonia flow correctly. This is important because the nozzle blockages and leaks in ammonia lines may cause the disability of an ammonia feeding line. The set point of ammonia slip seems to have significance in the performance of the controller. The response of the ammonia slip measurement is significantly faster than the response of the NO_x measurement. Thus, it can be used as a feedback better than the NO_x emission measurement. The performance of ammonia slip predictor was also tested during the tuning period. It is presently disabled, because the prediction accuracy was not good enough. Ammonia slip predictor isn't needed for the dead time compensation because the controller seems to react fast enough without it. According to the tuning period, it seems that ammonia should always be added in the case of disturbance, although the disturbance would go to the direction which should decrease the NO_x formation.

After the tuning was done, and the last minute changes were programmed to the logic, it was possible to start comparing the performance of the first controller configuration and the PLC. At first, the InTouch version was used, and the responses of the PLC were only observed. It was ensured that the responses of the PLC went to the right direction, and the ammonia need suggested by the PLC was at the same level as the ammonia need suggested by the InTouch version. When it became evident that the PLC provides similar responses as the InTouch version, and some minor modifications were done, it was PLC's turn to take over the control of ammonia injection. The ammonia slip predictor was for the time being left outside the PLC. The unbalance correction and the level correction were included, but only the unbalance correction could be tested. Level correction was disabled because of the blocked nozzle in the ammonia line 2.

5.3.2 Performance Test of the Controller

The duration of the performance test period was five days. During that time, the new ammonia pumps were in the use and the ammonia injection was controlled by the PLC. The aim was to demonstrate the improvement of the ammonia injection control compared to the old system. The performance was observed via remote control. The results can be seen from the collected process data directly, and they can also be calculated from the data.

In Appendix XX is shown the emission trend during the performance tests. From the emission trend, it can be seen that during the tests the NO_x emission has decreased, as well as its deviation. The base level of the ammonia slip may have slightly increased, but the deviation of the slip has certainly decreased. Although the boiler load has fluctuated, and some disturbances have occurred, the controller has been able to maintain the low emission level and to provide steady ammonia flow. This means that the controller's ability to tolerate disturbances is good and the controller performance is robust.

On the other hand, the results can be calculated from the process data. In Appendix XXI are shown the NO_x emissions during the performance tests compared to normal emission data. From Appendix XXI can be seen that the deviation of NO_x emission is quite different with the old system than with the new system. The calculated average of NO_x emission during the test is 52 mg/Nm^3 and the standard deviation of the emission is 6 mg/Nm^3. Thus, the NO_x emission with the new ammonia feeding equipment is 23 % smaller than with the old ammonia feeding equipment. The standard deviation of the NO_x emission with new equipment is 83 % smaller than with the old equipment. This proves that the adaptive controller has been able to reduce the NO_x emission peaks. Here, it must be reminded that the performance test period is short when compared to the whole data aqcuisition time. In the long run, the results can be somewhat different. Anyhow, on the basis of the performance tests, it can be said that the new ammonia feeding equipment has succeeded to fulfill the expectations.

6. CONCLUSIONS AND PROPOSALS

NO_x formation in the fluidized bed combustion of biofuel has not been sufficiently studied. The most studies are concentrated on coal combustion. It can be assumed that the reactions are similar in the biofuel combustion, but further studies are required. It seems that the most significant process values in the NO_x formation are boiler load, air distribution, flue gas recirculation flow and CO concentration. With higher boiler load, the temperatures, stream velocities and flue gas flow increase, which increases the NO_x emissions significantly. Flue gas recirculation seems to have an interaction with the NO_x emission. At the Brista Kraft power plant, the flue gas recirculation flow fluctuates constantly regardless of the steady load. The control of flue gas flow could be improved so that the flue gas amount will be changed only in load transition situations as the bed temperature also changes. This could help to even up the NO_x -emission.

6.1 Boiler Unbalance

The unbalance of the boiler has an effect on the NO_x formation. From the emission measurement results, it can be seen that the boiler has been in the unbalance. In the presence of extra O_2, more NO_x will be formed and more ammonia is needed. If the unbalance could be more easily detected, the corrective actions could be taken and the NO_x emission could also be decreased. The best way to detect the boiler unbalance would be a CO measurement of the flue gas located in the flue gas channel. The boiler unbalance is generally caused by uneven fuel feed. If the fuel feed cannot be improved, the CO measurement would be worth considering, because the boiler unbalance has many other undesirable effects in addition to the increased NO_x emission.

6.2. Hybrid SNCR/SCR System

The hybrid SNCR/SCR system has been working particularly well, but some modifications can be recommended. If it were possible, it would be feasible to shorten the ammonia line from the main ammonia pump to the ammonia feeding points. The coriolis-based ammonia flow measurement isn't the most reliable measuring equipment at the low flow rates. More accurate measurement would be recommendable, as the ammonia flow measurement brings essential information about the performance of the hybrid SNCR/SCR. The piston pumps have been suitable for the testing purposes, but control valves might be more reliable in the long run as they don't need that much maintenance. The main ammonia pump is able to produce such pressure that control valves could be used instead of piston pumps. The advantage of using piston pumps is that the transportation pressure of harmful ammonia can be kept low. Control valves produce more even flow, which would be better for ammonia hoses than the pulsatile flow produced by the piston pumps. The ammonia injection nozzles seem to block very easily, particularly when they aren't in the use. Some other kind of a nozzle would be worth considering, or the cleaning of the ammonia nozzles with the pressurized air should be improved. Manual cleaning of the nozzles is an unpleasant procedure due to the possible ammonia leak.

6.3 Ammonia Injection Controller

The present ammonia injection controller seems to perform well although it has not as many features as was planned. The most important improvement is the use of ammonia slip as the feedback because the ammonia slip measurement is significantly faster than the NO_x measurement. The set point for ammonia slip has been very useful in defining the ammonia slip, which can be allowed when the NO_x emission is decreased. The cost optimization by the NO_x emission charge and ammonia price would bring the further improvement to the ammonia slip integration. The blocked nozzle delayed the tests of the level correction part, which could have brought some additional improvement to the controller performance. The whole controller must be designed so that it will feed ammonia even if input value is missing due to a fault in a process measurement. The user interface of the controller has already been configurated to the DCS. The aim is that the controller would feed the ammonia so that the operators don't need to interfere it.

6.4 Suggestions for Further Studies

Fuzzy logic has been quite useful in the ammonia injection application. Potential for other local fuzzy solutions should be studied. The optimization of the whole power plant process with the advanced control methods would bring numerous advantages, but it is more economical to apply these control methods in such parts of the process which really need improvement. For example optimizing limestone feed in a SO_2 abatement system would be such an application. In future, the advanced control methods will be more generally used, and further study of these methods would be profitable.

The formation of nitrogen oxides has been widely studied, but the work seems to be endless as the chemical reactions in the boiler furnace cannot be reliably predicted. The interactions between different process values and NO_x formation are complex, and their modeling is difficult. Proper NO_x formation models could be useful in many ways. Especially, the fluidized combustion of biofuels requires more research as it becomes more popular way of energy production. Another way of energy production, which needs to be studied, is combustion of waste fuel in the CFB boiler. The emissions from the waste combustion are even more difficult to predict and model. The hybrid SNCR/SCR concept is not widely used, and studies about it are difficult to find. The hybrid SNCR/SCR seems to be very effective way to reduce NO_x emissions, and it can be recommended especially if the NO_x emission limits will be tightened. The catalyst regeneration is worth of studying, as the extension of the catalyst lifetime will decrease the costs of the catalyst replacement.

7. SUMMARY

The aim of this thesis was to reduce the NO_x emissions of the CFB boiler at the power plant of Brista Kraft Ab. Because the emissions of the CFB boiler are considered low to start with, it seemed that the emissions can be reduced only by cutting down the occasional NO_x peaks which appear mostly during disturbances in the boiler operation. Improvements to the ammonia feeding equipment and to the ammonia injection control were chosen as the most effective way to reduce the emissions. The ammonia feeding equipment was improved so that it became possible to control ammonia injection to the each of the ammonia feeding points. New piston pumps were installed to the each of the four ammonia lines.

Process data was collected to find out which parameters cause the NO_x emission, and to study the combustion process itself. The modified ammonia feeding equipment was tested to study the effects of uneven ammonia distribution on the NO_x emission. Simultaneously, the NO_x emissions before the catalyst were measured. The gathered information was used in constructing a fuzzy logic-based adaptive controller. Fuzzy logic was chosen, because it does not need the traditional model including a transfer function and the dead time. Traditional model for the NO_x formation is too difficult to be used in this context. Instead of the traditional model, the fuzzy logic uses a kind of heuristic black-box model, which can be identified with the process measurements. Another advantage of the fuzzy logic is when a one-sided proportional control must be build. The control actions will be taken only if the observed value changes to a certain direction.

The new controller was tested at the power plant, and a trial run of the controller was performed to prove its efficiency in reducing the NO_x -emissions. Although all the available features of the controller weren't in use, the NO_x emissions were reduced over 20 % and the standard deviation of the emission was reduced over 80 %. Thus, it seems that the objective of the project was reached.

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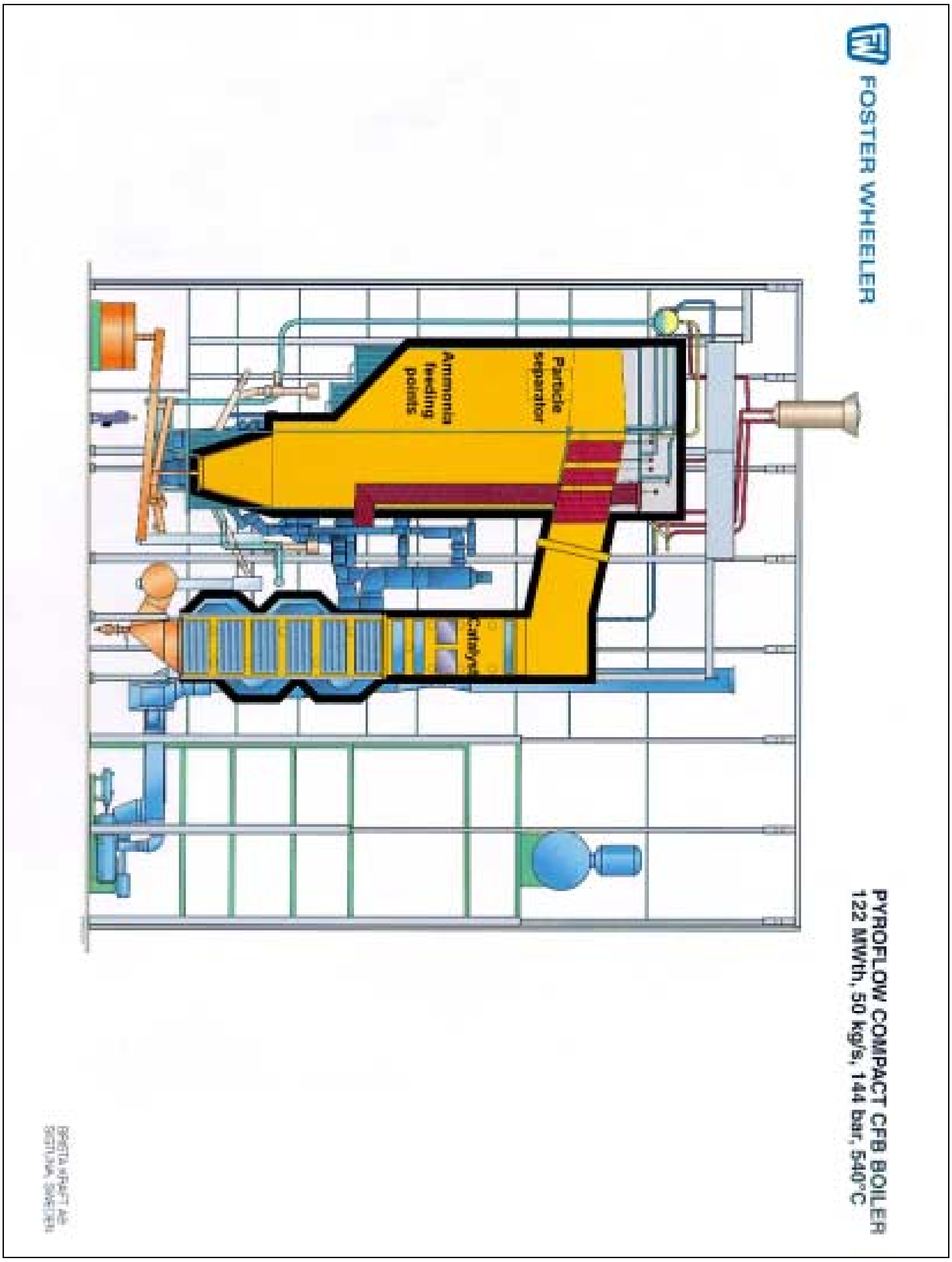
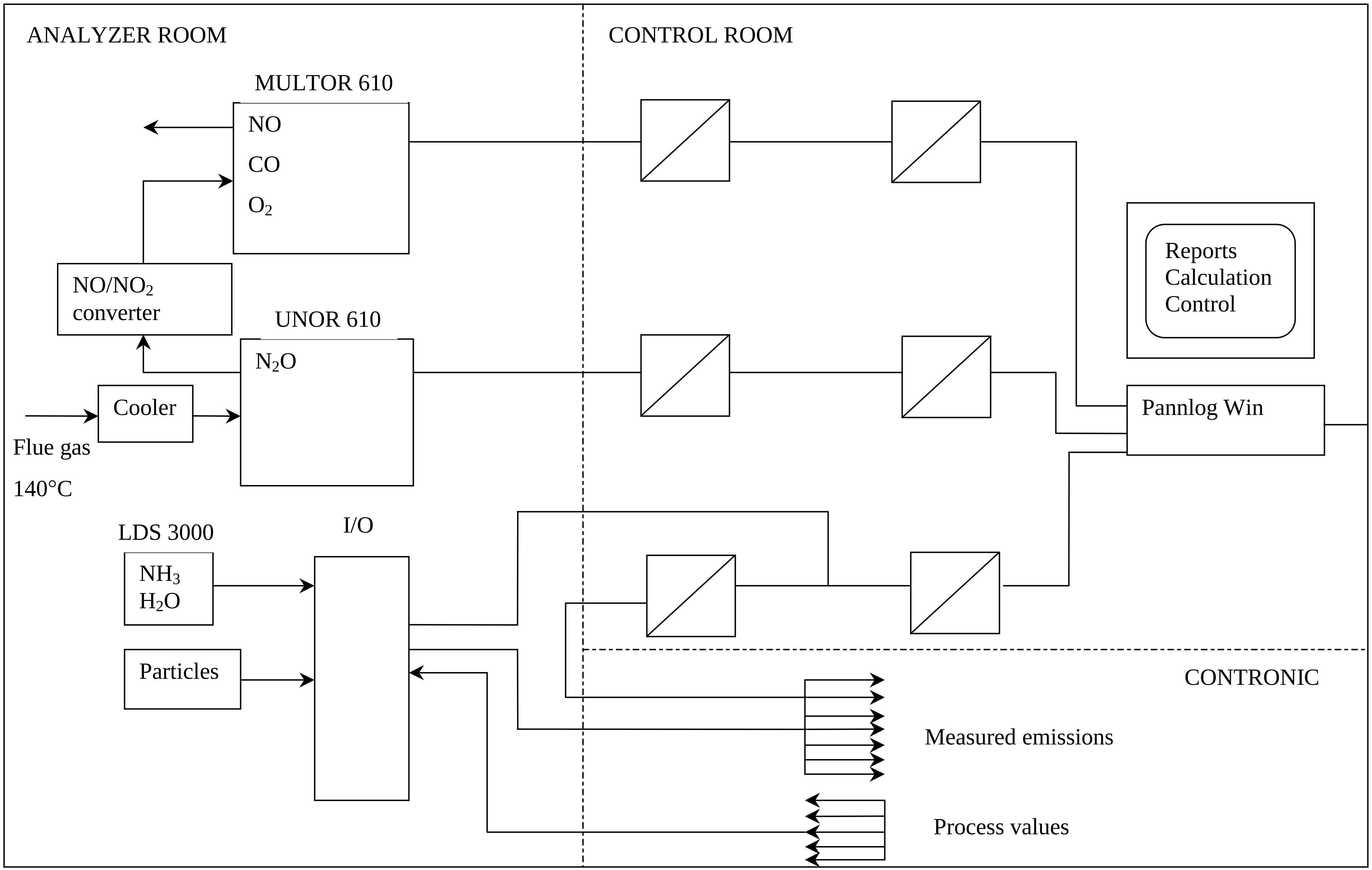
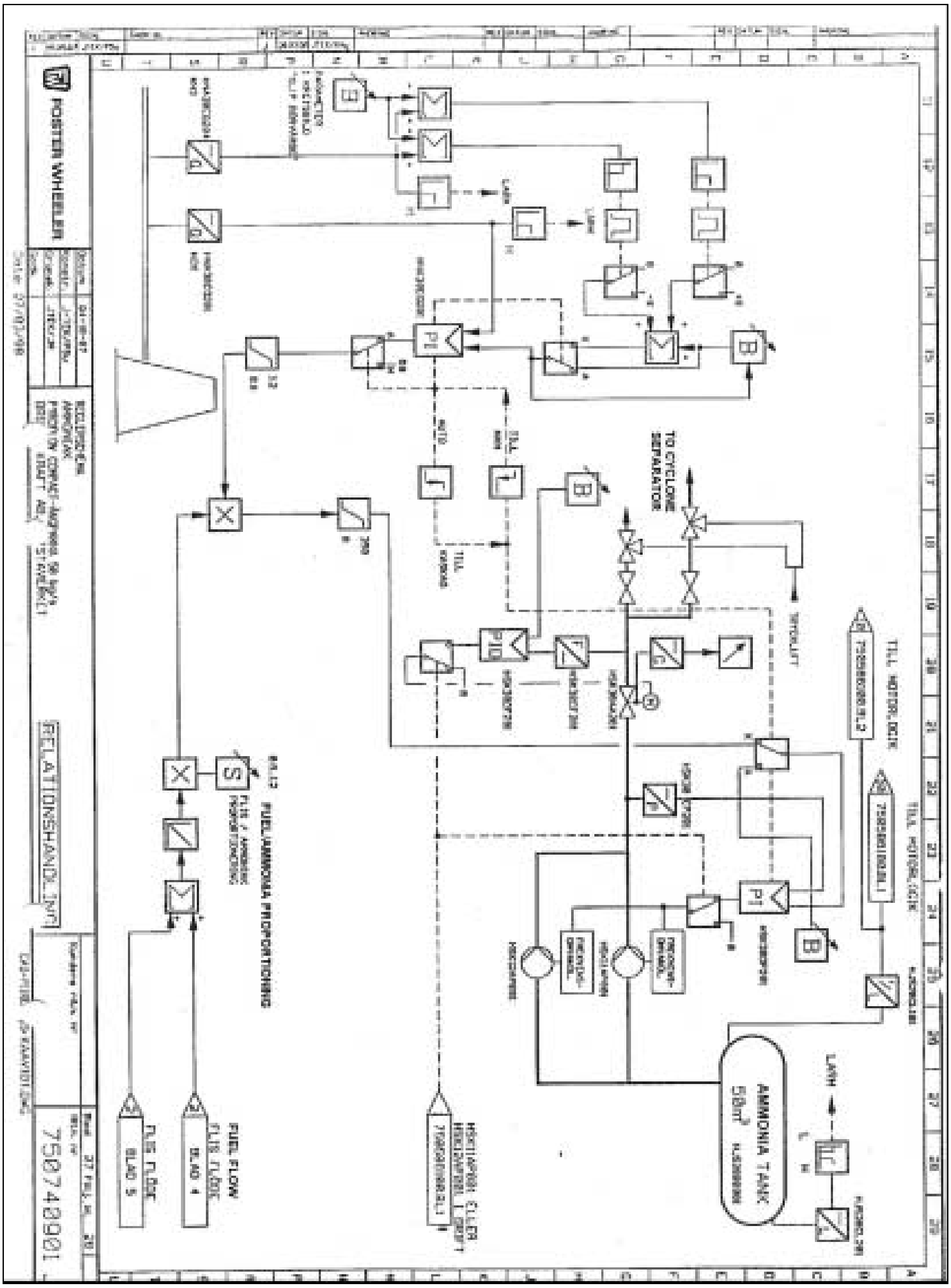
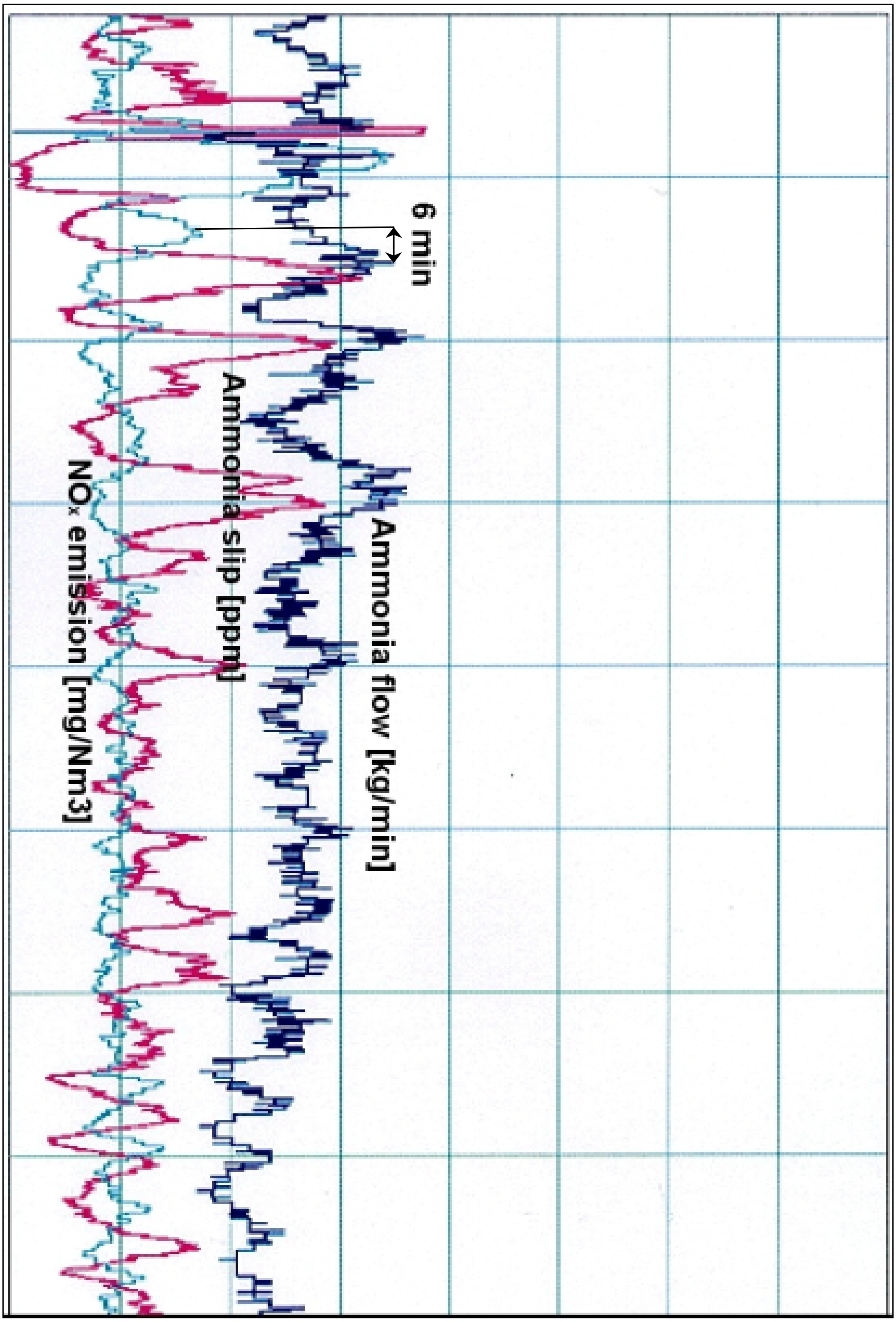
APPENDIX I


FOSTER WHEELER
Particle separator
Ammonia feeding points
Catalyst
PYROFLOW COMPACT CFB BOILER
122 MWth, 50 kg/s, 144 bar, 540°C

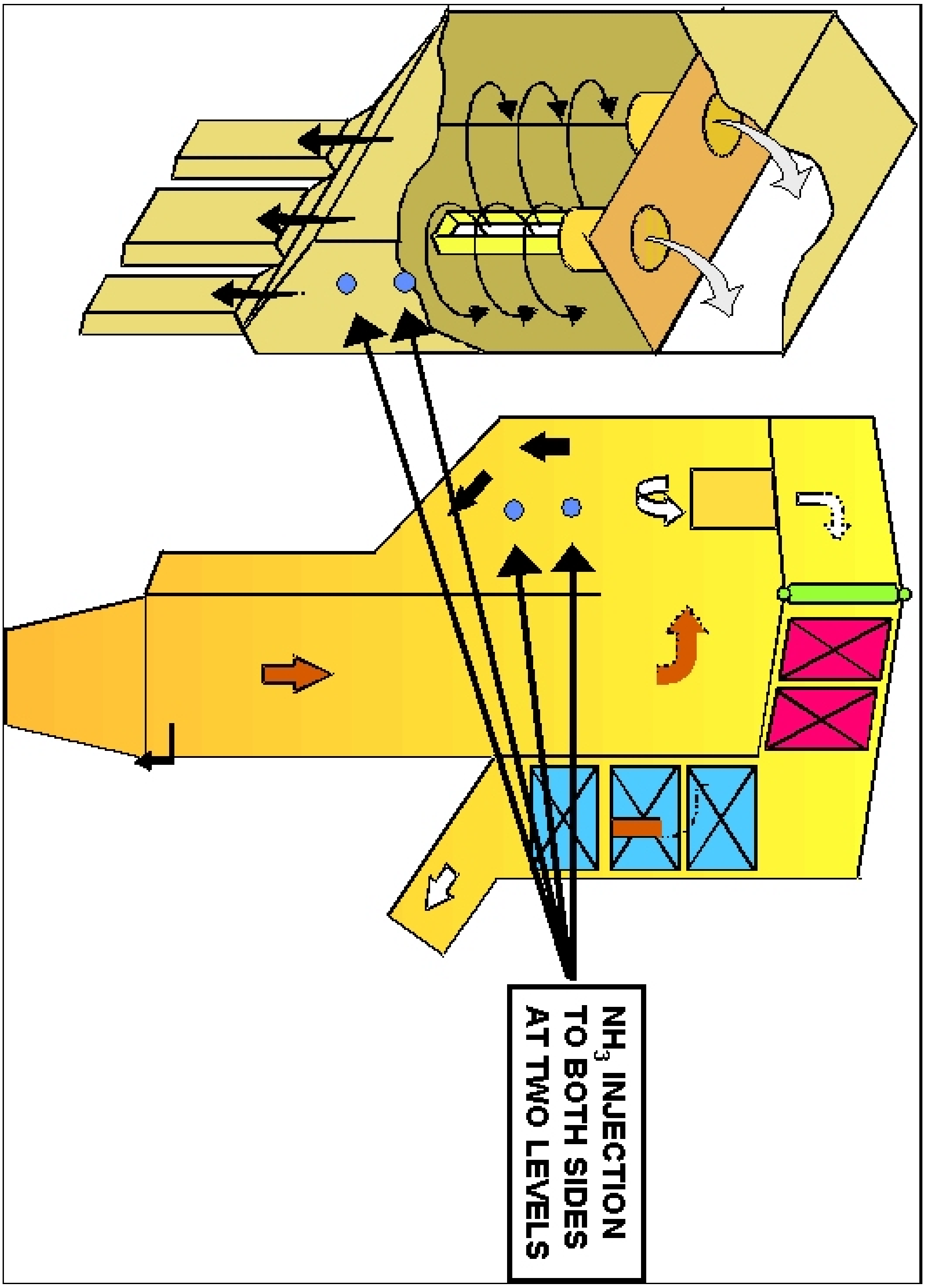

ANALYZER ROOM
CONTROL ROOM
MULTOR 610
NO
CO
O2
NO/NO2
converter
UNOR 610
N2O
Cooler
Flue gas
140°C
LDS 3000
NH3
H2O
Particles
I/O
Reports
Calculation
Control
Pannlog Win
CONTRONIC
Measured emissions
Process values

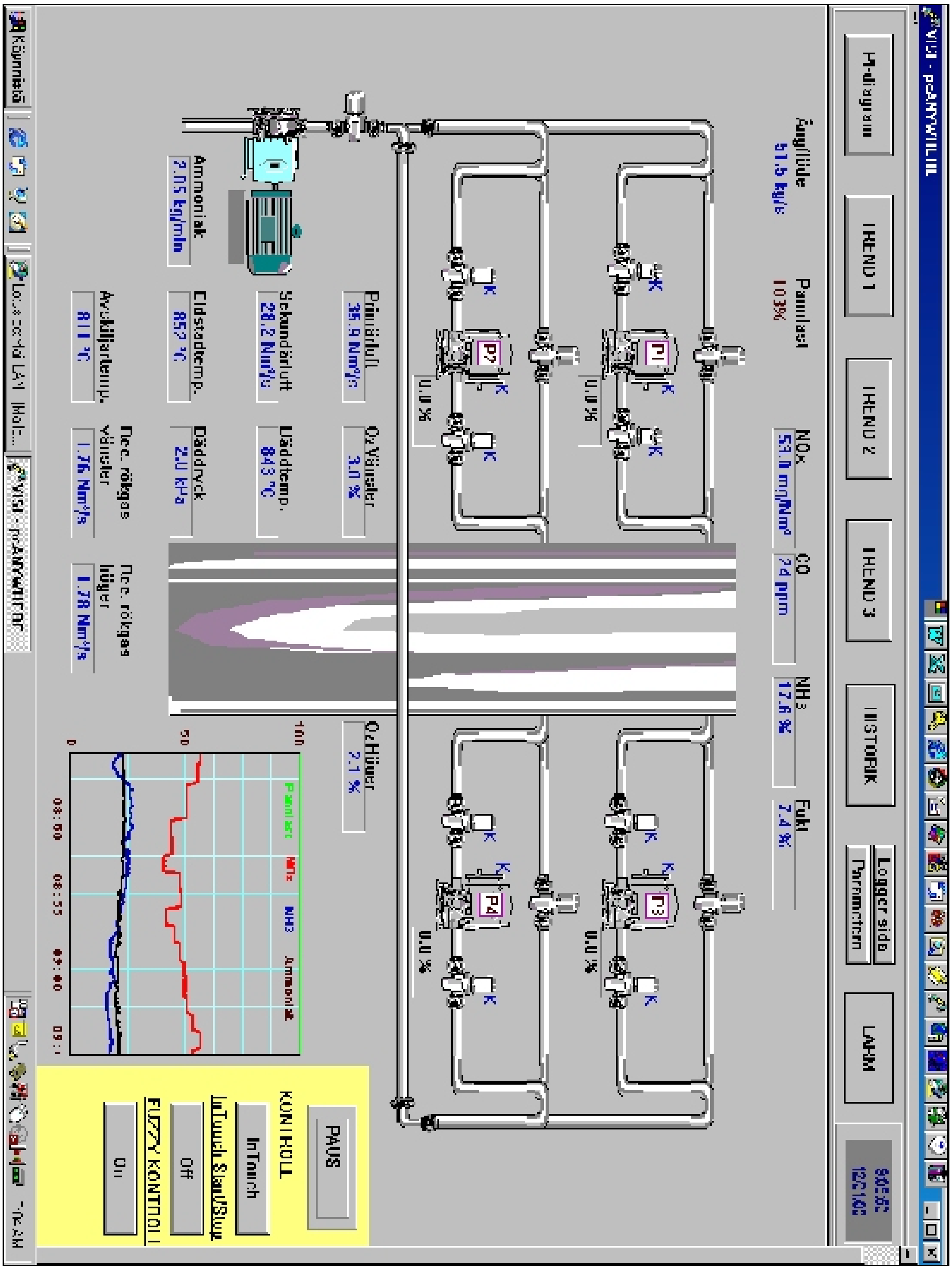
APPENDIX III




6 min
Ammonia flow [kg/min]
Ammonia slip [ppm]
NOx emission [mg/Nm3]

APPENDIX V



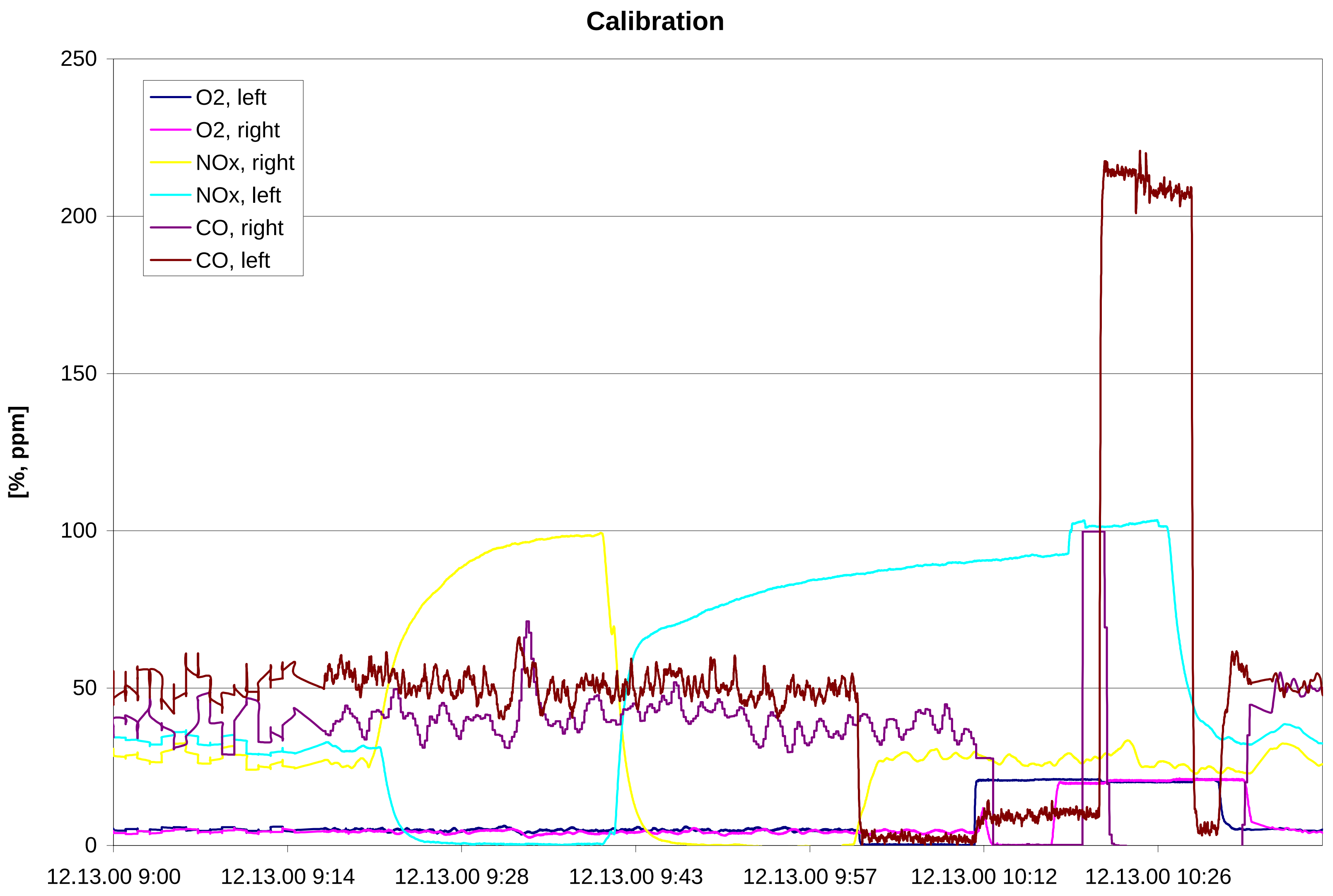

TREND 1
TREND 2
TREND 3
HISTORIK
LARM
Logger sida
Parametrar
Ångflöde
51.5 kg/s
Pannlast
103%
NOx
CO
24 ppm
NH3
17.6 %
Fukt
7.4 %
Ammoniak
2.05 kg/min
Primärluft
35.9 Nm³/s
Sekundärluft
28.2 Nm³/s
Eldstadstemp.
852 °C
Bäddtemp.
843 °C
Bäddtryck
2.0 kPa
O2 Vänster
3.0 %
O2 Höger
2.1 %
PAUS
KONTROLL
InTouch
Off
On
FUZZY KONTROLL

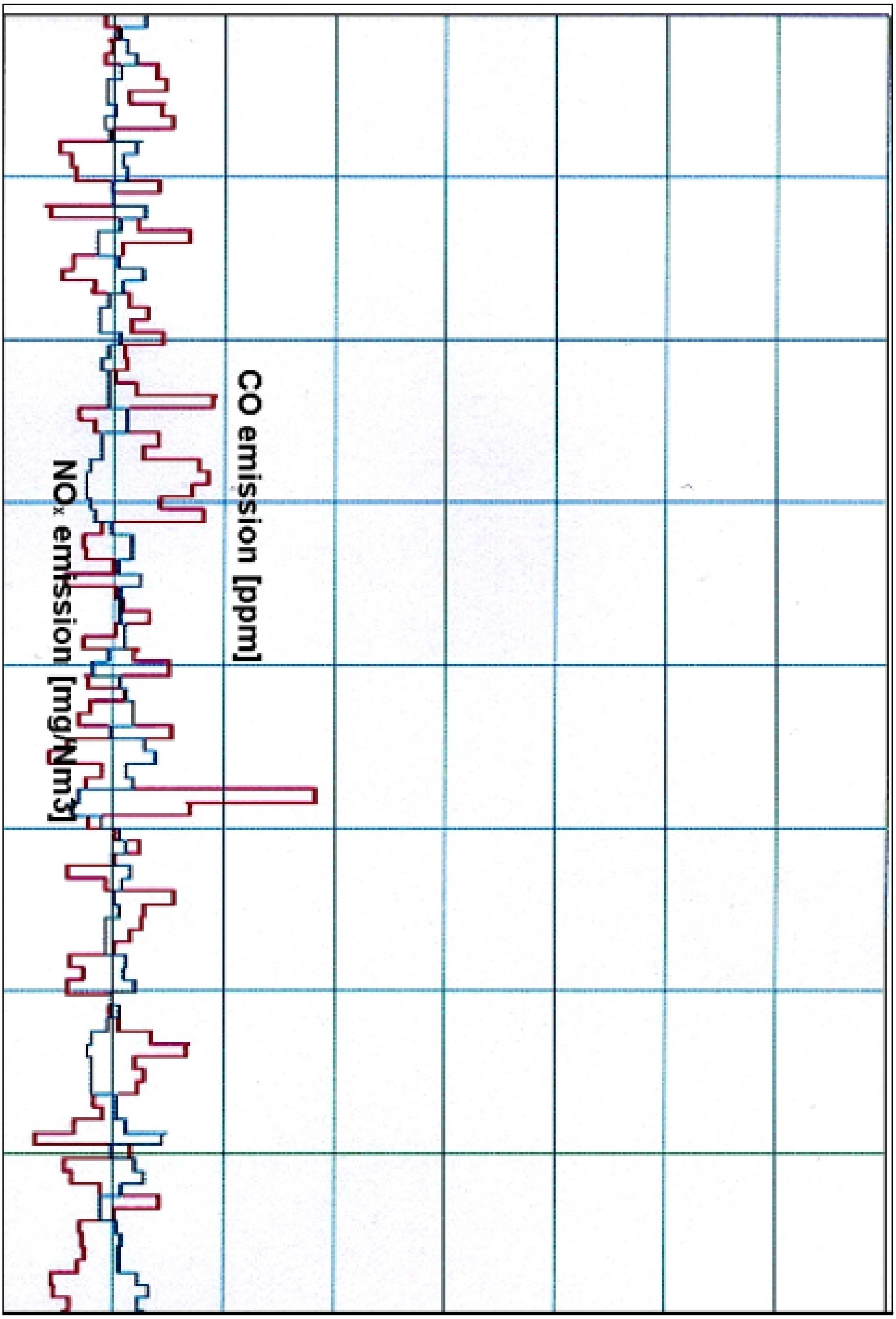
Load 100 % = 50 kg/s	Codes		Dates
Pump 1	A1		18.12.00 at 11.05-13.05
Pump 2	A2		19.12.00 at 13.00-15.00 and 18.12.00 at 13.05-15.05
Pump 3	A3		12.12.00 at 15.00-17.00
Pump 4	A4		18.12.00 at 15.30-17.30
Pumps 1 and 3	A13	upper level	15.12.00 at 7.30-9.30
Pumps 2 and 4	A24	lower level	19.12.00 at 11.00-15.00 and 14.12.00 at 8.45-11.00
Pumps 1, 2, 3 and 4	A1234		15.12.00 at 9.30-11.25
Without ammonia injection	A0		12.12.00 at 17.25-18.30

Load 75 % = 37,5 kg			
Pump 1	B1		14.12.00 at 15.00-17.00
Pump 2	B2		12.12.00 at 13.05-15.05
Pump 3	B3		12.12.00 at 11.05-13.05
Pump 4	B4		14.12.00 at 12.50-15.00
Pumps 1 and 3	B13	upper level	15.12.00 at 11.25-13.30
Pumps 2 and 4	B24	lower level	15.12.00 at 13.30-15.25
Pumps 1, 2, 3 and 4	B1234		20.12.00 at 12.00-14.00
Without ammonia injection	B0		14.12.00 at 17.10-18.10

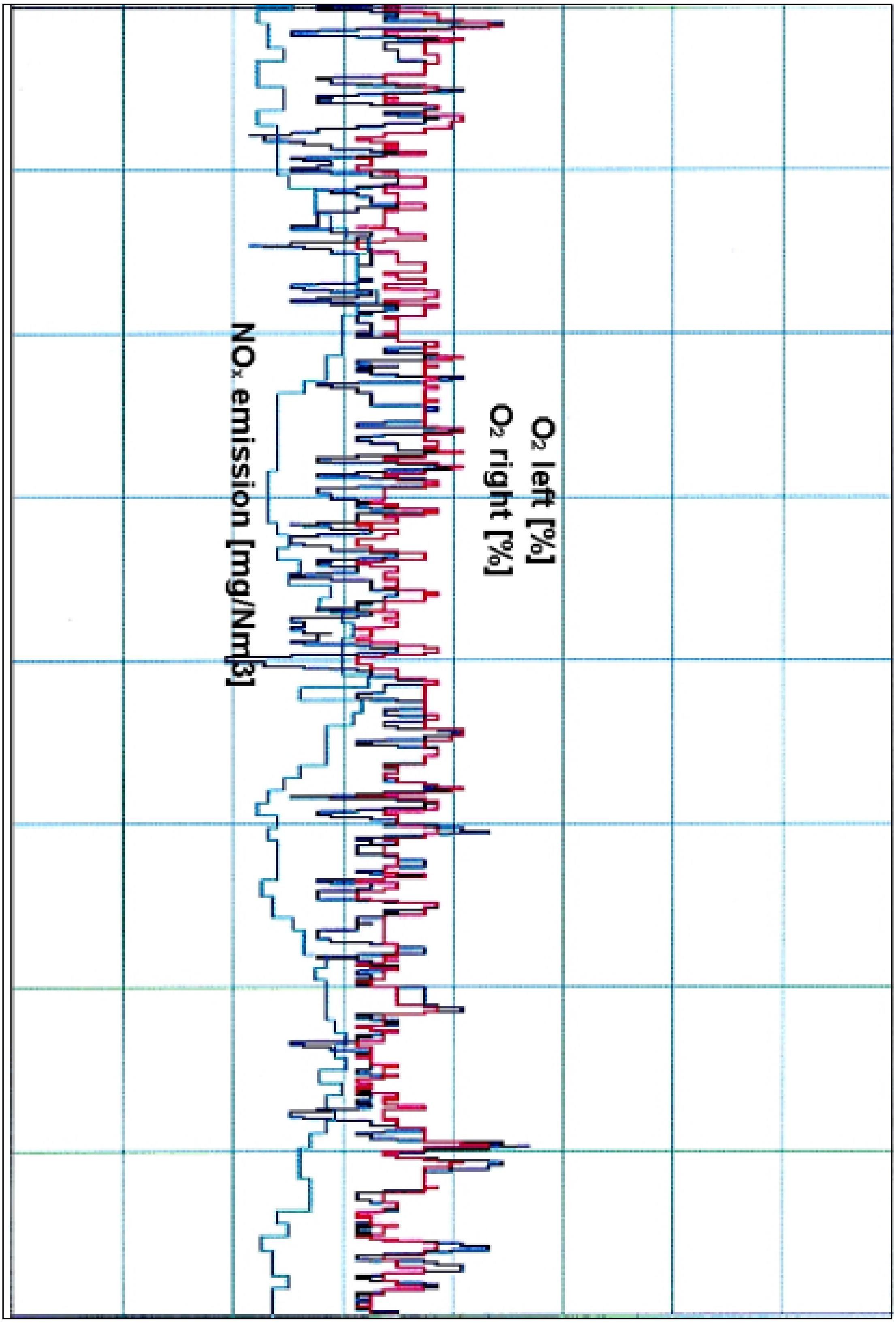
Load 50 % = 25 kg/s			
Pump 1	C1		
Pump 2	C2		
Pump 3	C3		13.12.00 at 14.30-16.30
Pump 4	C4		
Pumps 1 and 3	C13	upper level	13.12.00 at 12.30-14.30
Pumps 2 and 4	C24	lower level	
Pumps 1, 2, 3 and 4	C1234		
Without ammonia injection	C0		13.12.00 at 16.50-17.50

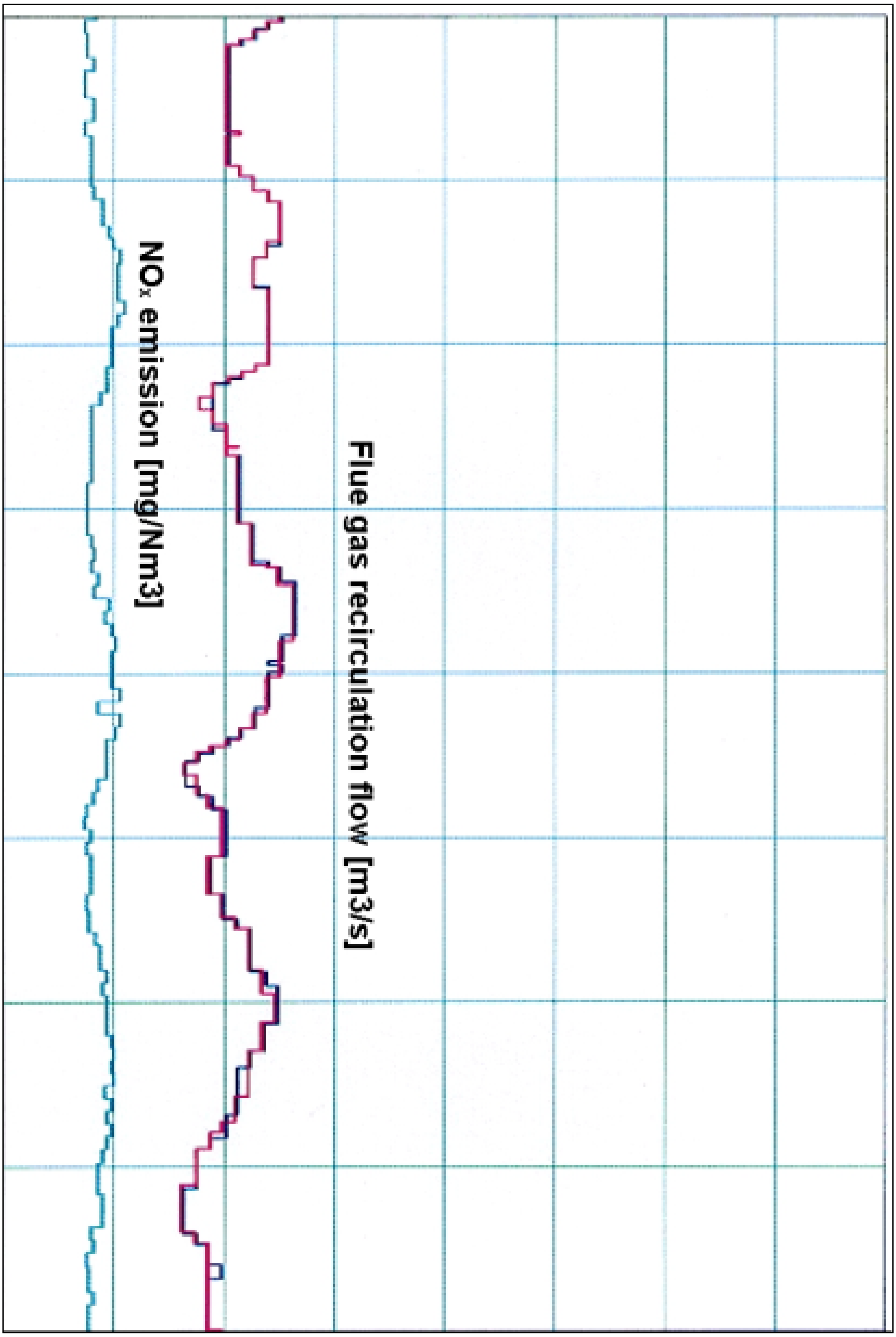
APPENDIX VIII

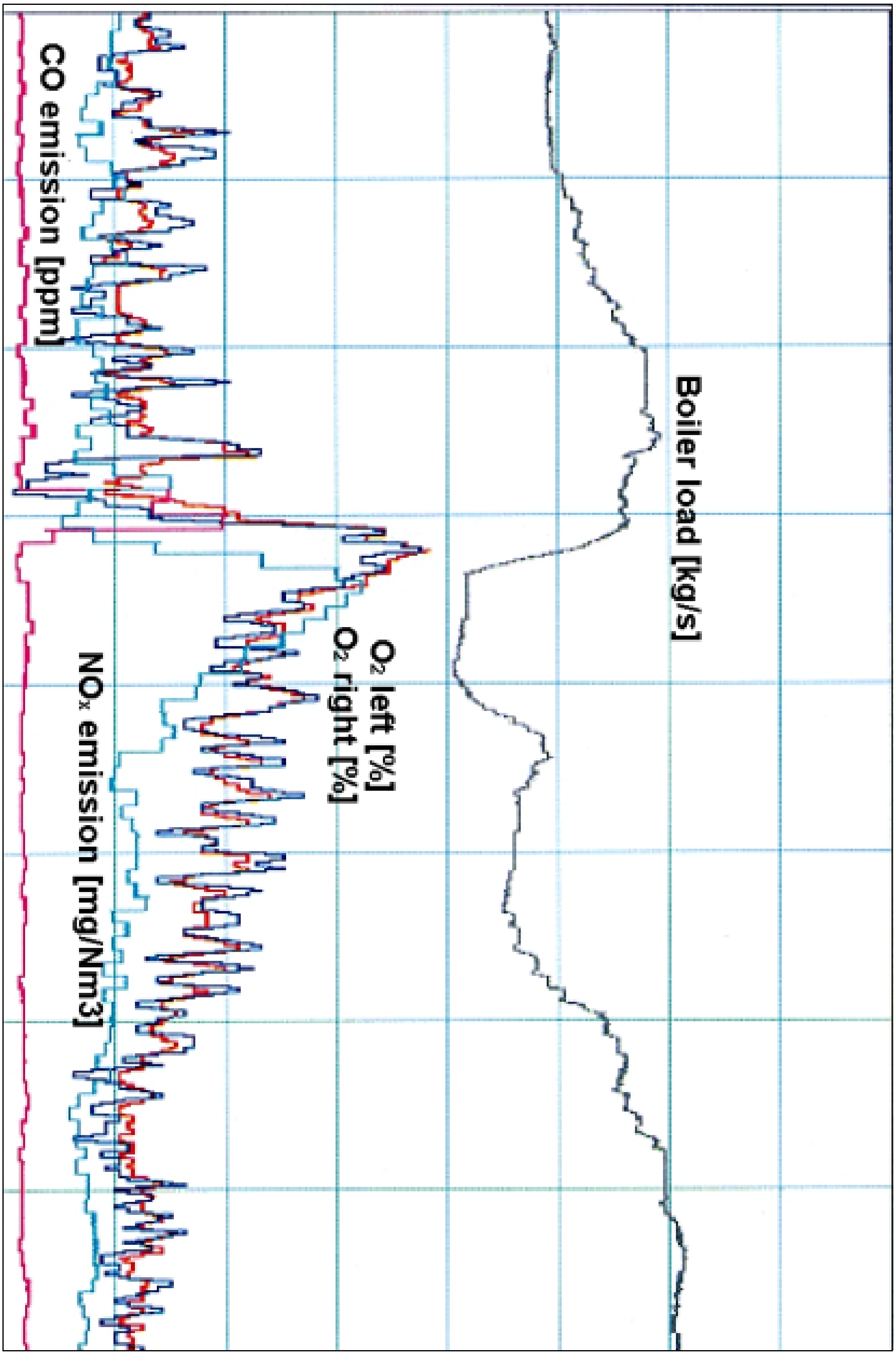



CO emission [ppm]
NOx emission [mg/Nm3]

APPENDIX X

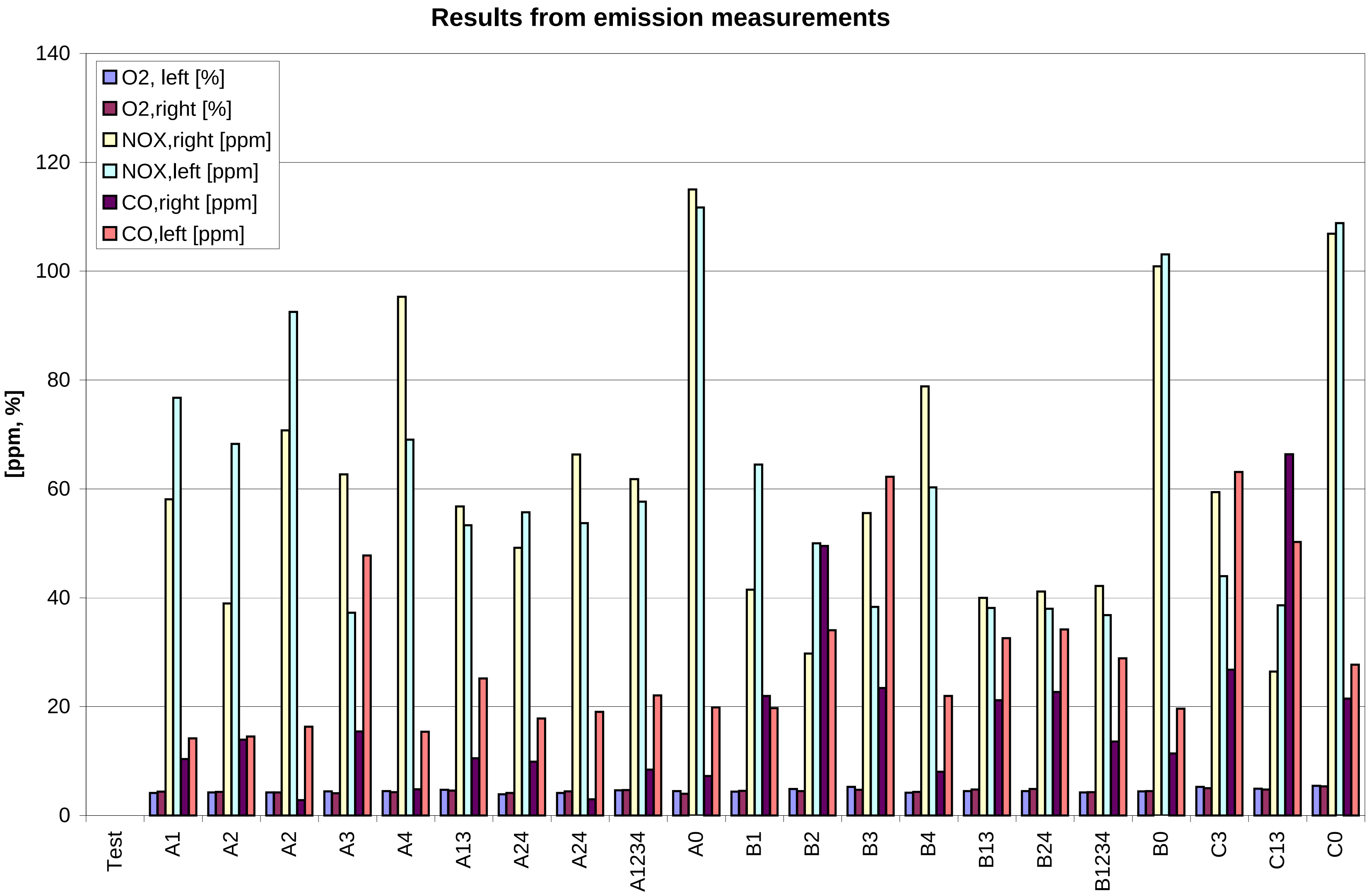



NOx emission [mg/Nm3]
Flue gas recirculation flow [m3/s]


Boiler load [kg/s]
O2 left [%]
O2 right [%]
NOx emission [mg/Nm3]
CO emission [ppm]

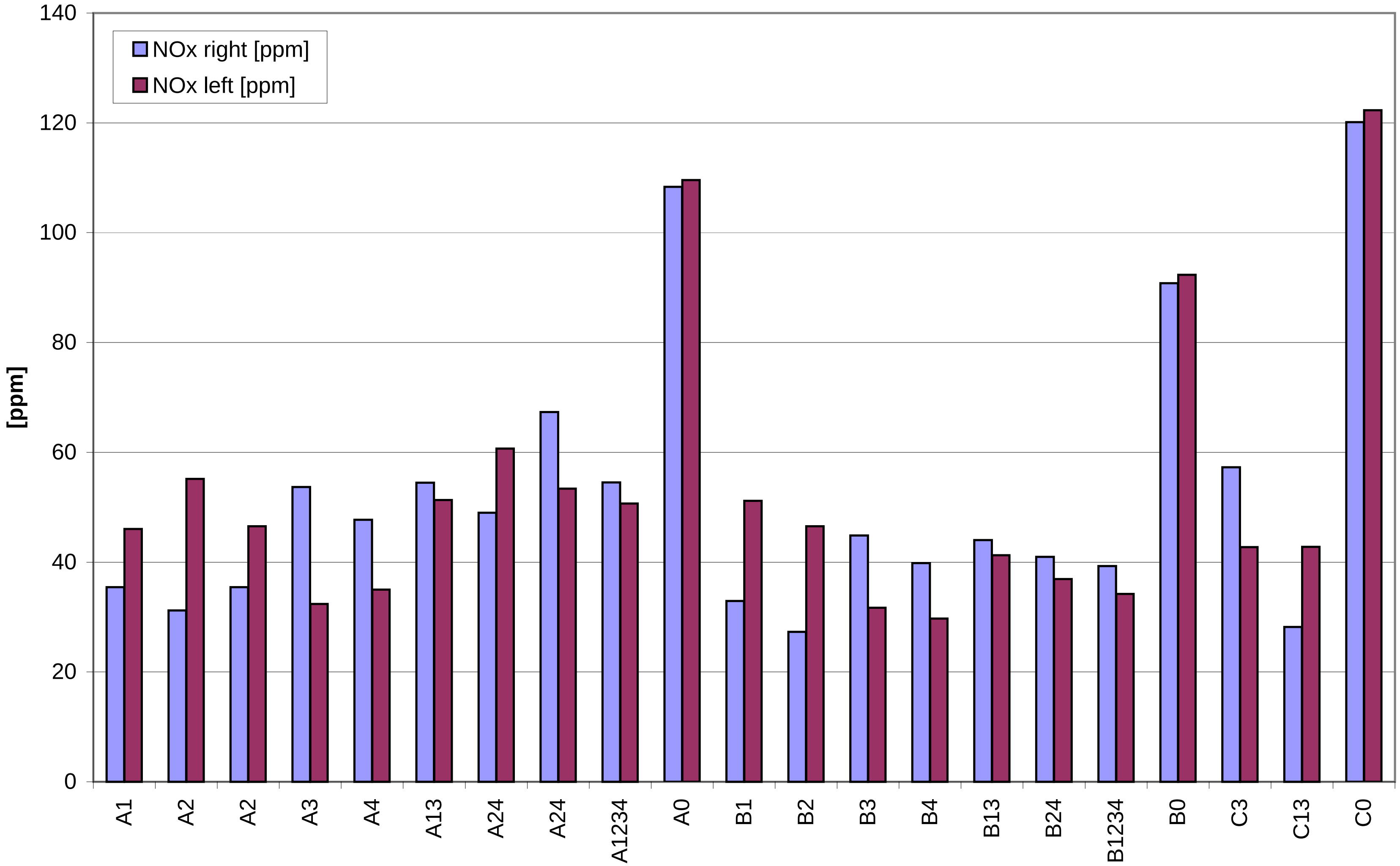
	O_2, left [%]		O_2,right [%]		NO_X,right [ppm]		NO_X,left [ppm]		CO,right [ppm]		CO,left [ppm]		
Test	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	
A1	4,13	0,22	4,38	0,29	58,08	3,88	76,74	3,42	10,39	0,80	14,19	0,54	
A2	4,26	0,29	4,34	0,38	38,97	7,57	68,26	5,54	13,91	1,71	14,49	0,56	18.12.
A2	4,26	0,23	4,24	0,32	70,73	4,47	92,53	3,94	2,82	0,59	16,30	0,40	19.12.
A3	4,45	0,28	4,07	0,43	62,68	8,37	37,26	3,02	15,46	4,92	47,76	9,96	
A4	4,46	0,27	4,26	0,31	95,28	4,12	69,06	2,89	4,81	1,08	15,41	0,76	
A13	4,72	0,50	4,56	0,64	56,80	5,85	53,31	4,30	10,51	3,38	25,20	3,23	
A24	3,90	0,35	4,14	0,43	49,17	27,45	55,72	17,76	9,87	7,47	17,80	3,01	14.12.
A24	4,13	0,30	4,42	0,37	66,32	4,27	53,70	4,57	2,97	0,59	19,03	0,96	19.12.
A1234	4,64	0,27	4,69	0,36	61,77	3,92	57,64	3,60	8,43	1,27	22,04	1,38	
A0	4,50	0,23	4,01	0,34	115,01	6,12	111,70	6,93	7,27	0,63	19,85	0,80	
B1	4,40	0,25	4,53	0,34	41,50	14,72	64,47	7,30	21,97	4,87	19,73	1,08	
B2	4,88	0,29	4,47	0,37	29,74	6,01	50,00	5,80	49,53	9,47	34,02	7,54	
B3	5,24	0,51	4,75	0,45	55,57	4,87	38,33	2,50	23,42	3,35	62,25	4,32	
B4	4,19	0,35	4,33	0,45	78,85	8,93	60,26	9,42	8,02	1,52	21,95	4,19	
B13	4,48	0,33	4,76	0,46	39,99	4,70	38,15	3,72	21,17	4,37	32,58	4,23	
B24	4,48	0,25	4,86	0,33	41,15	2,80	38,00	1,78	22,71	2,89	34,17	2,90	
B1234	4,25	0,25	4,28	0,35	42,16	5,03	36,83	4,12	13,57	2,17	28,87	2,72	
B0	4,42	0,33	4,48	0,40	100,91	5,63	103,11	5,11	11,39	1,23	19,63	0,75	
C3	5,24	0,43	5,03	0,50	59,39	10,25	44,00	4,87	26,79	7,97	63,13	8,35	
C13	4,91	0,34	4,79	0,42	26,43	10,25	38,60	10,66	66,38	12,46	50,28	11,03	
C0	5,48	0,55	5,36	0,61	106,91	39,25	108,82	34,69	21,48	23,72	27,69	14,17	

APPENDIX XIII

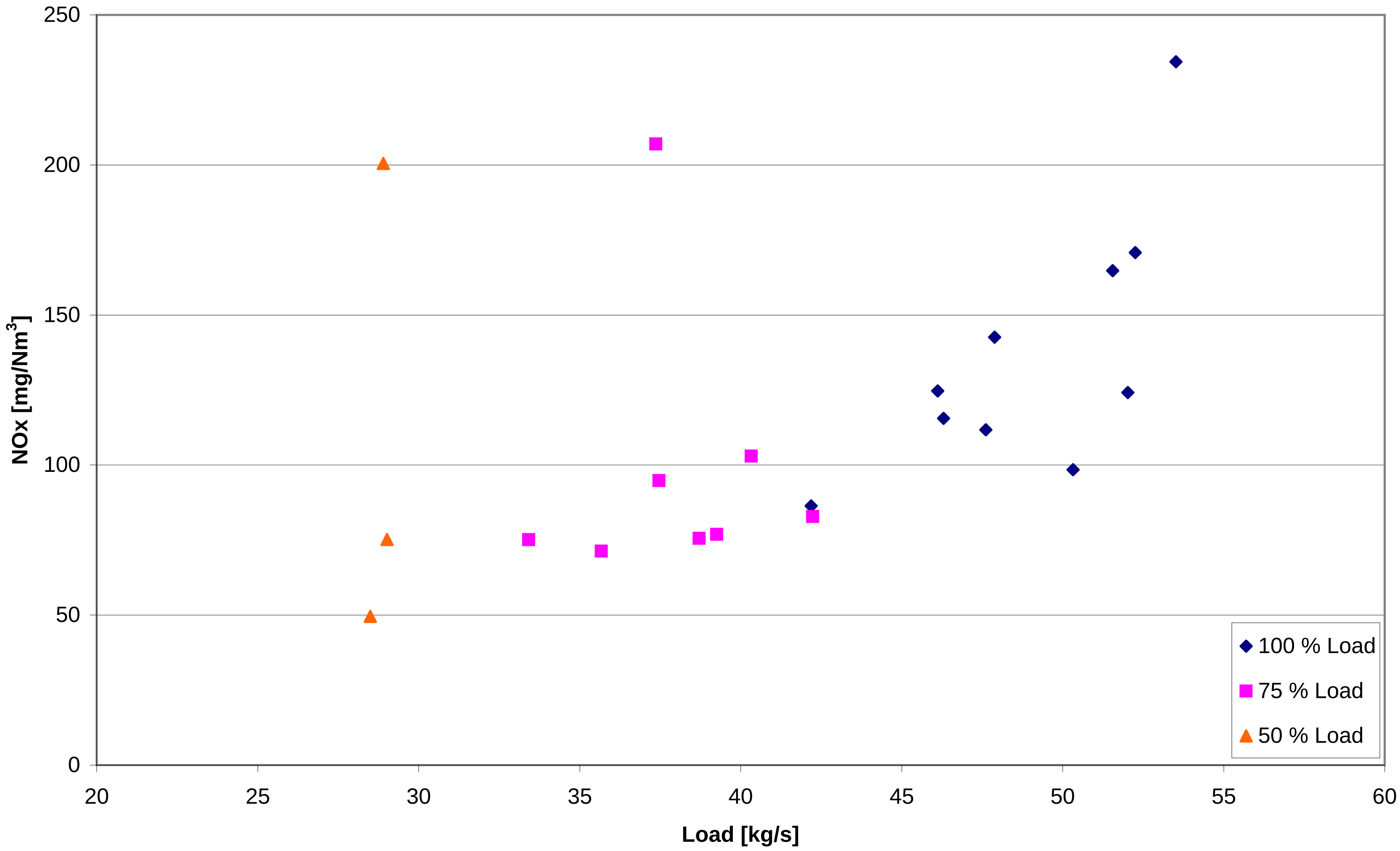


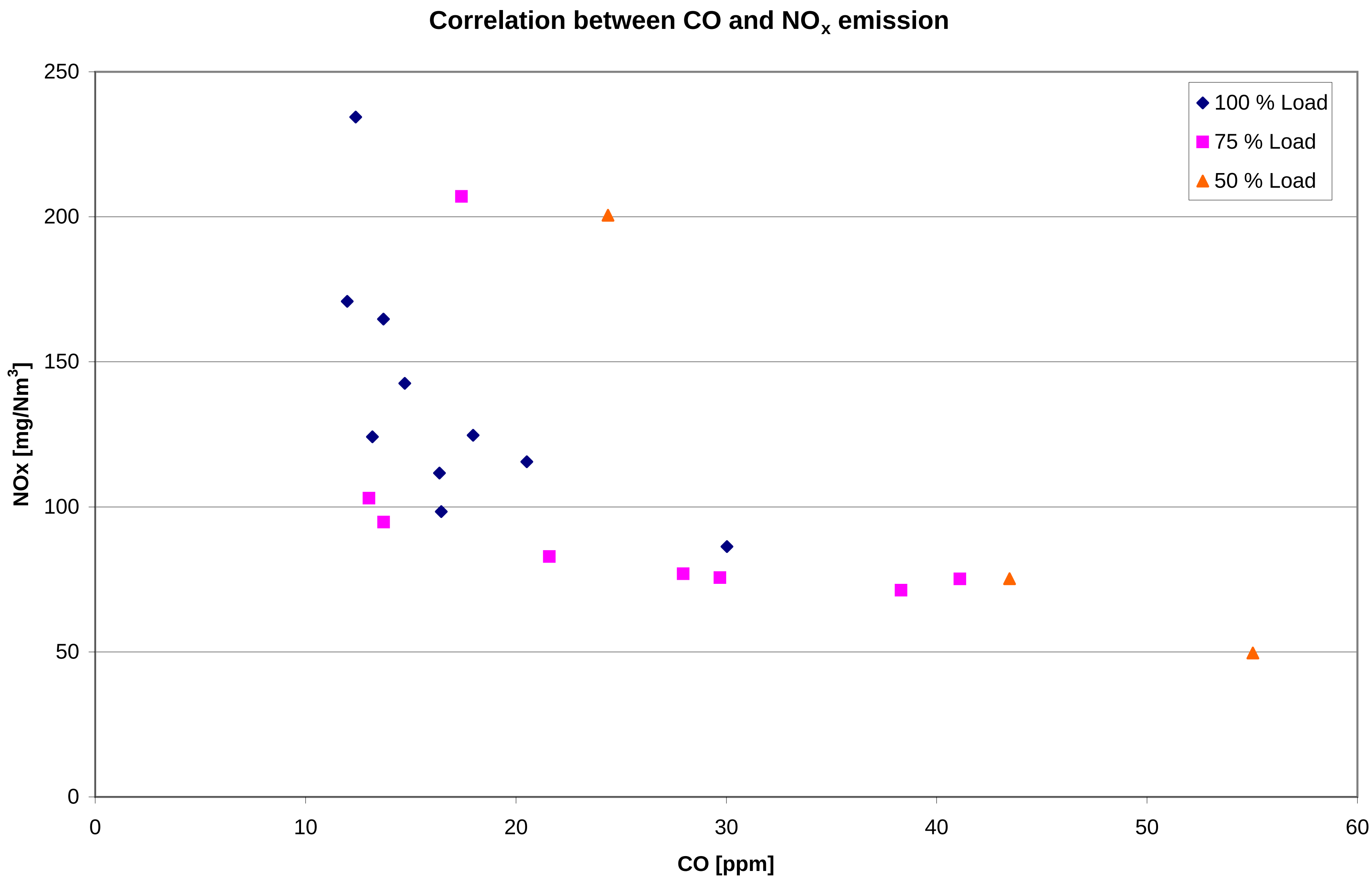
APPENDIX XIV

Reduced measuring results



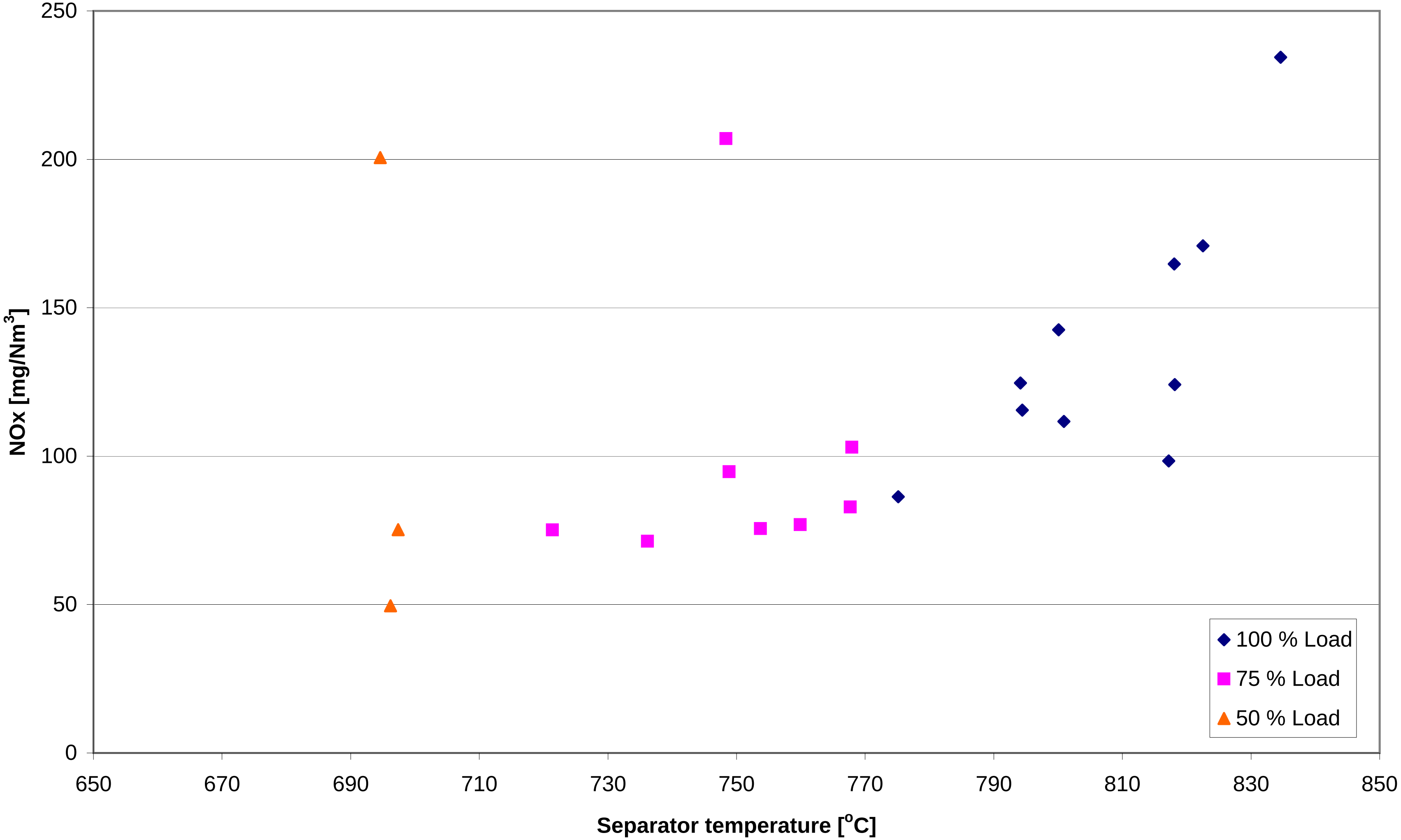
Correlation between load and NO_x emission

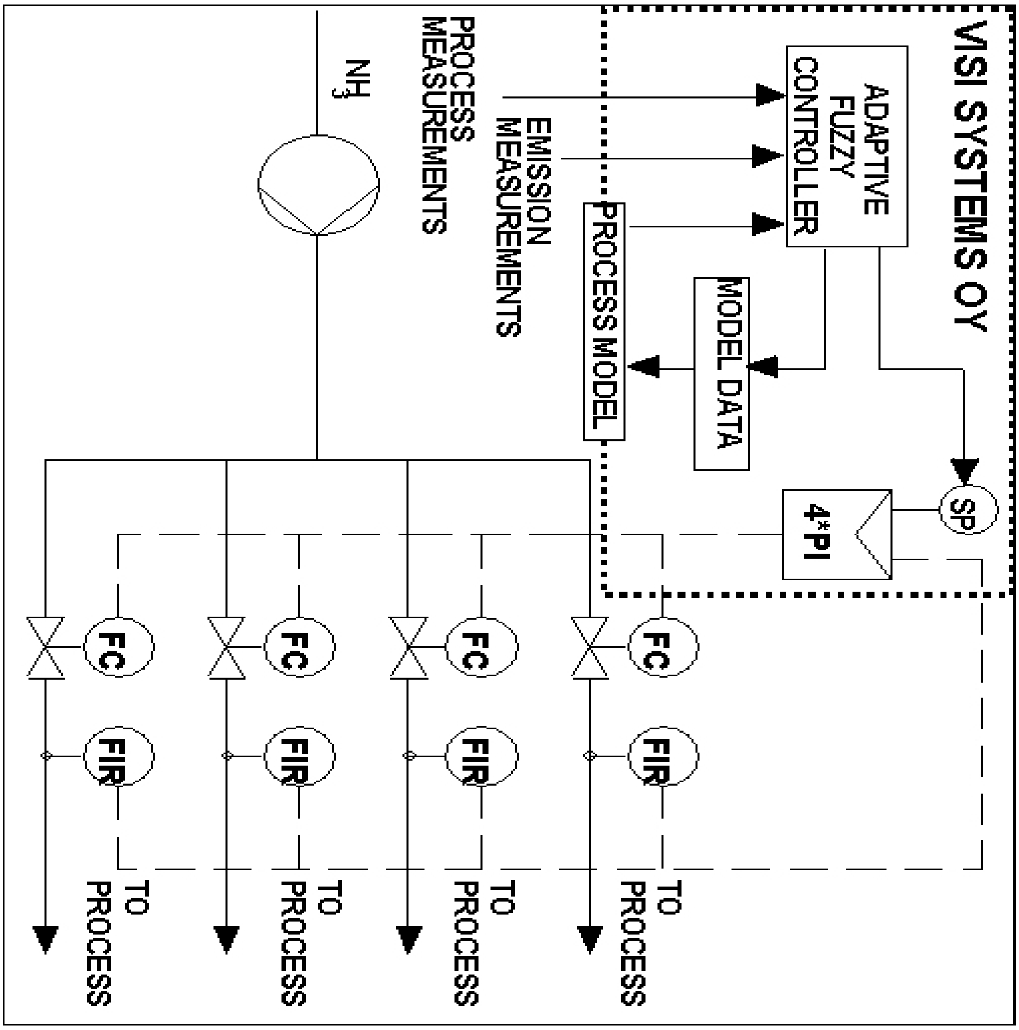


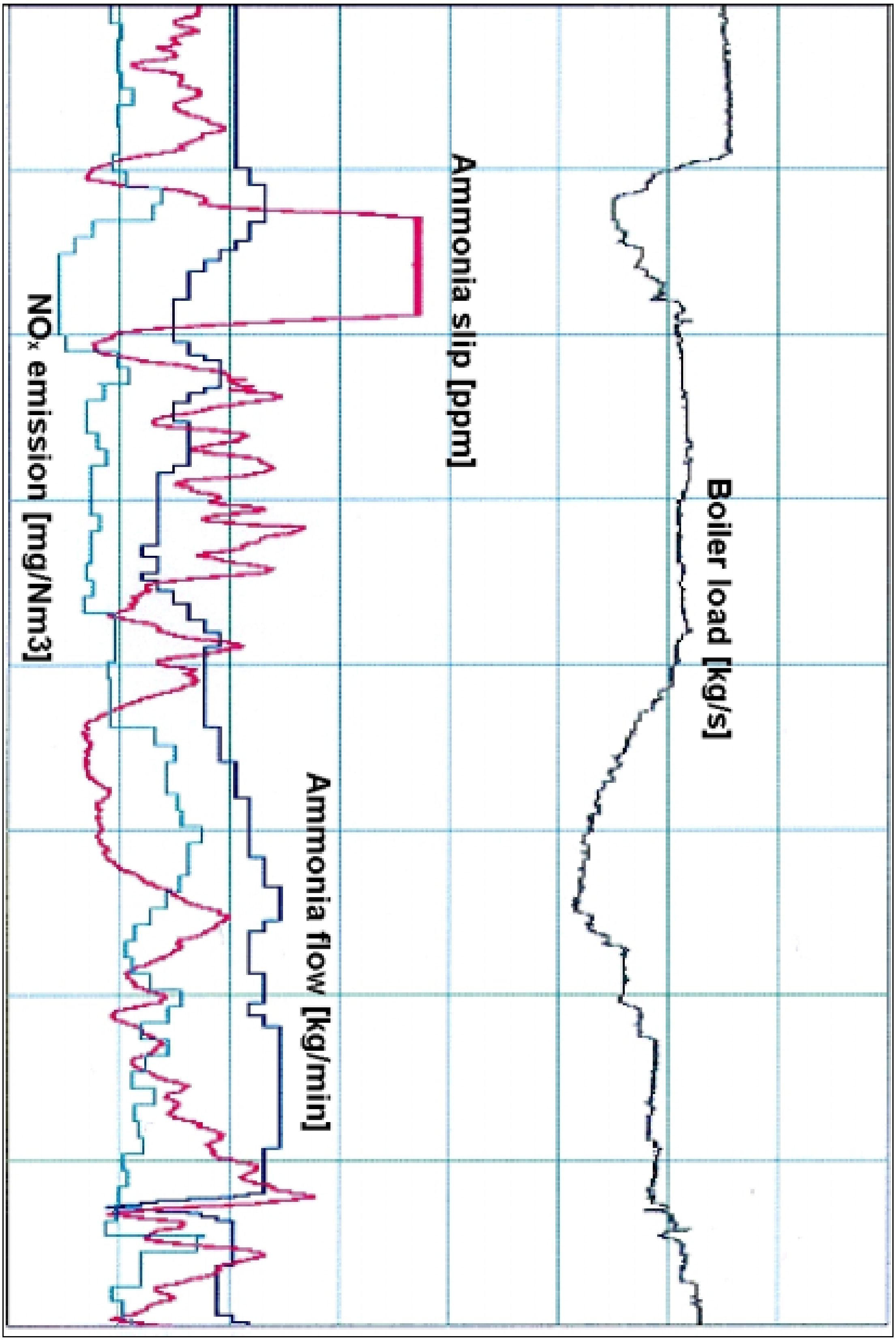

Correlation between CO and NOx emission
250
200
150
100
50
0
NOx [mg/Nm3]
0
10
20
30
40
50
60
CO [ppm]
100 % Load
75 % Load
50 % Load

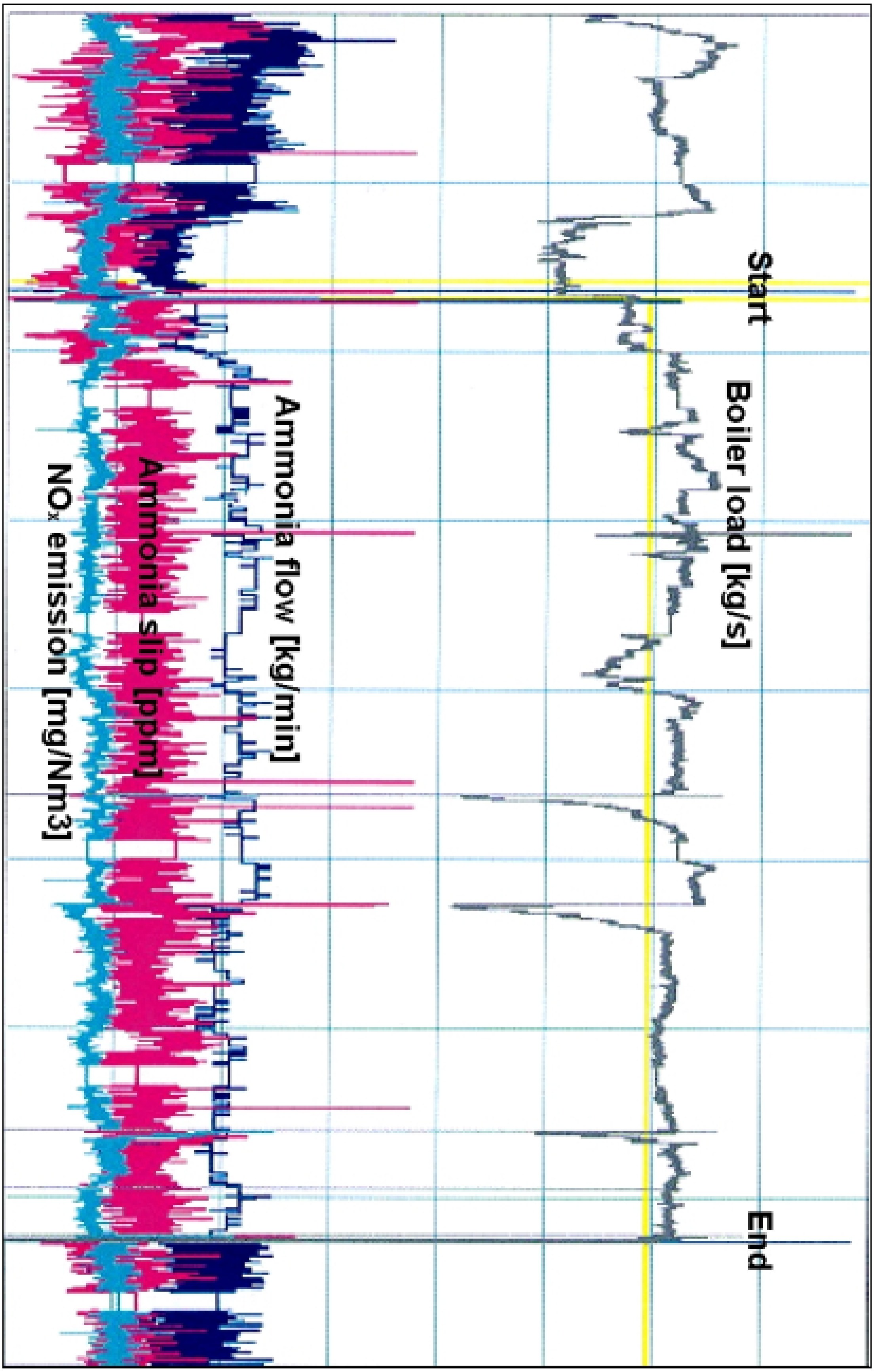
APPENDIX XVII

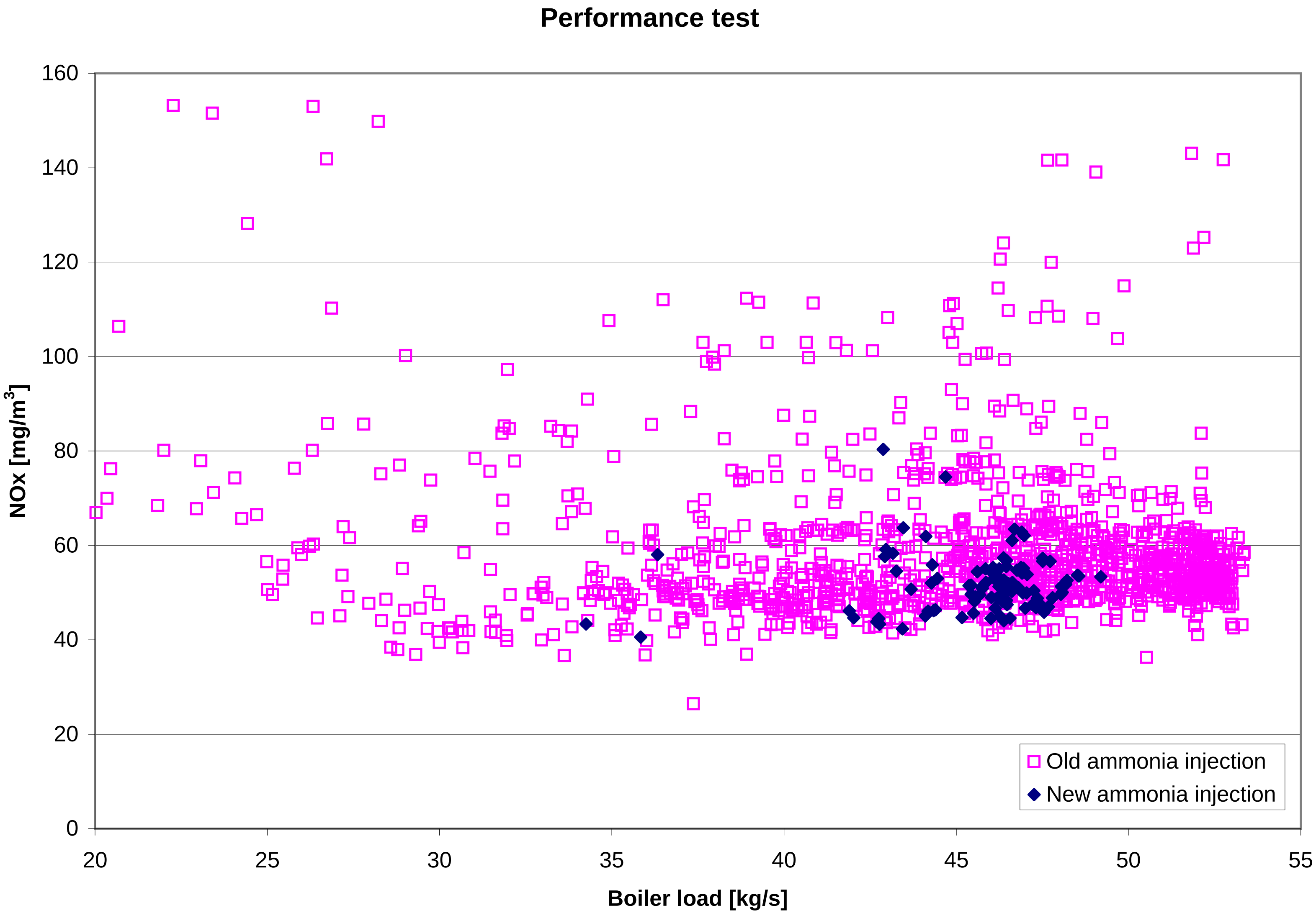
Correlation between particle separator temperature and NO_x emission




VISI SYSTEMS OY
ADAPTIVE FUZZY CONTROLLER
PROCESS MEASUREMENTS
EMISSION MEASUREMENTS
PROCESS MODEL
MODEL DATA
NH3
SP
4*PI
FC
FC
FC
FC
FIR
FIR
FIR
FIR
TO PROCESS
TO PROCESS
TO PROCESS
TO PROCESS


Boiler load [kg/s]
Ammonia slip [ppm]
NOx emission [mg/Nm3]
Ammonia flow [kg/min]


Start
End
Boiler load [kg/s]
Ammonia flow [kg/min]
Ammonia slip [ppm]
NO_x emission [mg/Nm3]



Performance test
160
140
120
100
80
60
40
20
0
NOx [mg/m^3]
20
25
30
35
40
45
50
55
Boiler load [kg/s]
Old ammonia injection
New ammonia injection