ADVANCED CONTROL OF AN INDUSTRIAL CIRCULATING FLUIDIZED BED BOILER USING FUZZY LOGIC

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OULU 2000

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Academic Dissertation to be presented with the assent
of the Faculty of Technology, University of Oulu, for
public discussion in Raahensali (Auditorium L 10),
Linnanmaa, on February 4th, 2000, at 12 noon.

OULUN YLIOPISTO, OULU 2000

Manuscript received 3 January 2000
Accepted 10 January 2000

Communicated by
Doctor Timo Hyppänen
Doctor Enso Ikonen

ISBN 951-42-5519-4

ALSO AVAILABLE IN PRINTED FORMAT

ISBN 951-42-5518-6
ISSN 0355-3213 (URL: http://herkules.oulu.fi/issn03553213/)

OULU UNIVERSITY LIBRARY
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To Marja-Liisa, Anna-Kaisa and Markus

Karppanen, Erkki, Advanced control of an industrial circulating fluidized bed boiler using fuzzy logic
Department of Process Engineering, University of Oulu, FIN-90570 Oulu, Finland
2000
Oulu, Finland
(Manuscript received 3 January 2000)

Abstract

Circulating Fluidized Bed (CFB) boilers are widely used for multi-fuel combustion of waste and bio-fuels. When several non-homogeneous fuels, having varying heat values, are burned simultaneously, the boiler control system can be affected by various control challenges, especially since it is not feasible to reliably measure the energy content of the multi-fuel flow. In order to fulfill energy production needs and maintain the ability to burn low grade fuels, co-firing with high heat value fuels such as gas, oil or coal is needed.

Fuzzy Logic Control (FLC) has been successfully used for solving control challenges, where operators' process expertise can be transformed into automation. Real life control objects are often non-linear because the dynamics change with the operating point, or there might be other essential non-linearities in the combustion process.

The proposed fuzzy control applications were developed to solve control challenges the operators meet in daily operation of a 150 MW(th) CFB at Varenso Oy's (Stora Enso Oyj) K6 boiler in Varkaus Finland. Before implementing the applications in the fullscale boiler, they were tested at a 2 MW(e) pilot plant boiler at Foster Wheeler Energia Oy's Research Center in Karhula, Finland.

According to the industrial experiments, the four applications (steam pressure control, compensation of fuel quality fluctuation, fuel-feed optimization and increased bed inventory monitoring) discussed in this thesis, showed satisfactory performance and various improvements to the boiler control were achieved. Fuzzy logic control was shown to be a notable tool to improve the multi-fuel CFB boiler control.

Keywords: multi-fuel combustion, steam pressure control, optimization

List of symbols and abbreviations

Latin letters

a_1	coal price
a_2	waste fuel price
A`	fuzzy set
Ar	Archimedes number
b_1	coal heat value
b_2	waste fuel heat value
B^{l}	fuzzy set
C_{D}	resistance factor depending on Reynolds number
DE	change of error
d_{p}	surface-volume mean diameter of particles
E	error
$e(k)$	error
$e_{\mathrm{O}_2}(k)$	error of flue gas O_2
$\Delta e(k)$	change of error
F	fuzzy set
G	fuzzy set
g	gravity constant
$[H]$	hydrogen content of the analyzed sample
K_{D}	derivation gain
K_{I}	integration gain
K_{M}	process model steady-state gain
K_{P}	gain
l	rule in the rule base l=1,2,…,M
LE	linguistic value
M_{T}	fuel moisture
M	moisture of analyzed sample

N_e	scaling factor
$N_{\Delta e}$	scaling factor
N_u	scaling factor
NB	fuzzy set
NS	fuzzy set
$o(k)$	flue gas oxygen
$o_s(k)$	flue gas oxygen set-point
$p(k)$	steam pressure
$p_s(k)$	steam pressure set-point
$\Delta p(k)$	change of steam pressure
PB	fuzzy set
PS	fuzzy set
$q(k)$	steam flow
$\Delta q(k)$	change of steam flow
$Q_{\mathrm{net,v,m}}$	lower heat value in constant volume
$Q_{\mathrm{gr,v}}$	higher heat value in constant volume
r_{n}	set-point
r_{o}	radius of wet sphere
r_{p}	radius of pyrolysis zone
r_{wc}	radius of wet core
R	fuzzy relation
Re_{mf}	Reynolds number for minimum fluidization
S	Laplace transformer
S	power need set-point
T	process dead-time
T_{b}	bed temperature
T_{p}	pyrolysis temperature
T_{s}	control cycle
T_{wc}	wet core temperature
$u_2(k)$	control output
u_{n}	output
$u(k)$	control output
$\Delta u(k)$	change of control output
u_{mf}	minimum fluidization velocity
U	universe of discourse
U	output
U_{n}	other ROC’s output
u_{t}	terminal velocity for particle
V	universe of discourse
W_{n}	disturbance value
x	input, linguistic value
x_1	coal flow

x_2	waste fuel flow
y	linguistic value, crisp point, process value
$\bar{y}^l$	center of the fuzzy set
y_n	desired state of the process
y_sp	set-point
ZE	fuzzy set

Greek letters

ε_mf	void fraction in the bed
ϕ	sphericity of bed solids
μ	degree of membership
μ_F	degree of membership
μ_g	viscosity
ρ_g	density of the gas
ρ_S	density of the solid
τ	time constant
τ_F	controller time constant
τ_M	process model time constant

Abbreviations

BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
CFBC	Circulating Fluidized Bed Combustion
CIB	Coal In Bed sensor
CPC	Combustion Power Control
CYMIC®	Cylindrical Multi-Inlet Cyclone ®
DC	Disturbance Controller
DCS	Distributed Control System
DDE™	Dynamic Data Exchange
FBB	Fluidized Bubbling Bed
FBC	Fluidized Bed Combustion
FKBC	Fuzzy Knowledge-Based Control
FLC	Fuzzy Logic Control
FNN	Fuzzy Neural Network
IC	Inference Controller
INTREX™	Internal Heat Exchanger ™
ISC	Inferential Smith Predictor Control
ISO	International Organization for Standardization

MIMO	Multi-input Multi-output
MR	Model Reference
PI	Proportional Integral control
PID	Proportional Integral Derivative control
PV	Process Value
RC	Response Controller
ROC	Rate Optimal Control
TP	**TotalPlant®**

Acknowledgements

The work described in this thesis has been carried out as a research project in co-operation with Varenso Oy (Stora Enso Oyj) Varkaus, Finland (the power plant), Foster Wheeler Energia Oy Karhula, Finland (the Circulating Fluidized Bed boiler manufacturer's research center) and Honeywell-Measurex Varkaus, Finland (automation applications). The work was started during the spring of 1996 and continued through to the spring of 1998.

I wish to express my gratitude to the supervisor of my work: Professor Kauko Leiviskä, Department of Process Engineering, University of Oulu. Professor Leiviskä has continuously encouraged me and guided this work with great expertise during its different phases. The manuscript was reviewed by Doctors Enso Ikonen and Timo Hyppänen. Their valuable comments and critique are gratefully acknowledged. Thanks to Mrs. Hilary Ladd for editing the language of this thesis.

I am grateful to my colleagues at Honeywell-Measurex who have directly or indirectly supported my work. I wish to especially thank Messrs. Eero Joki-Korpela, Jarmo Kosunen and Jorma Tasa who gave me the opportunity to join this research project. Messrs. Heikki Pernu and Jali Matikainen did much of the practical work needed. I am greatly indebted to Researchers Ari Kettunen and Juha Tiensuu from the Foster Wheeler Research Center who gave invaluable support and guidance for this work. Additionally, I am thankful to the staff of the Varenso K6 boiler, to Messrs. Sauli Ekola, Seppo Kauranen, Ilmari Immonen, Marko Skyttä and Veijo Kainulainen as well as the K6 boiler operators, who gave valuable help during the industrial experiments.

The financial support provided by Savo High Technology Foundation and Honeywell-Measurex is gratefully acknowledged.

Finally, I wish to express my deepest gratitude to my wife, Marja-Liisa, for her support and love and to our children, Anna-Kaisa and Markus, for understanding that daddy can not always join in the fun and games.

Joroinen, 11 December 1999 Erkki Karppanen

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APPENDIX 1

1. Introduction

Automation system vendors, universities, research centers and the process industry continually strive to invent new and better methods to keep processes under control. The reason is evident. All companies must be competitive to survive. Better quality and performance, high availability and increased production at a lower cost are the targets to be achieved. Much research, on several kinds of applications, has been performed to fulfill the existing demands.

The development and terminology relating to control theory is historically denominated. Control theory can be classified (Hersh & Johnson 1997) to Classical Control Theory (1868-1950); Modern Control Theory (1960-1980), and Advanced Control Developments (ca 1975 onwards). The Advanced Control work is further divided into three activity groups. The first group contains robust optimal control, adaptive and self-tuning control and large-scale systems. In the second group are refined classical process control, multi-loop control, model-based predictive control, statistical process control and hierarchical supervisory control. Nowadays, many studied control methods like expert systems, fuzzy logic control, neural networks and knowledge-based systems, belong in the third group, which can be termed Intelligent Control. Although the link between theory and technology has not often been totally explicit, the above-mentioned advanced control methods have become common additions to conventional Proportional Integral Derivative (PID)-type control methods in the process industry.

This thesis discusses the possibilities and suitability of an intelligent control method such as fuzzy logic control in controlling and managing combustion performance of an industrial Circulating Fluidized Bed (CFB) boiler.

1.1. Circulating fluidized bed combustion in energy production

Fluidized bed combustion is not a new invention. In the 1920’s, a German scientist by name of Fritz Winkler introduced gaseous products of combustion into the bottom of a crucible containing coke particles (Basu & Fraser 1991, Hyppänen 1989). Since that time, the technical solution has continued to progress, but the development of solid fuel combustion in fluidized beds did not start heavily until the mid 1970's.

During the 1980's and 1990's, the Circulating Fluidized Bed Combustion (CFBC) process has gained great popularity (Basu & Fraser 1991, Grace *et al.* 1997). The main reason for the increased interest and growing number of installations is the CFB boiler's fuel flexibility and positive environmental influences. The advantages include high combustion efficiency, low NO_x and SO_2 emissions, and the ability to burn a wide variety of fuels, including very low grade fuels.

The number of CFB boilers has increased very rapidly. Currently, there are about 250 CFB boiler units either under construction or in operation worldwide. The total capacity is in excess of 15000 MW(e) (McCoy 1995). The overwhelming majority of total steam capacity for Fluidized Bed Combustor (FBC) projects worldwide is in co-generation and utility applications, comprising 55% and 30% of the total capacity, respectively. Small power, district heating and process steam applications comprise the remaining 15% of the total worldwide capacity equally (Grace *et al.* 1997).

Currently, the CFBC units are operating in more than 20 countries, with additional countries focusing on this technology to solve environmental, waste and fuel problems (Grace *et al.* 1997). The worldwide sale of the CFB boilers is depicted in Figure 1.

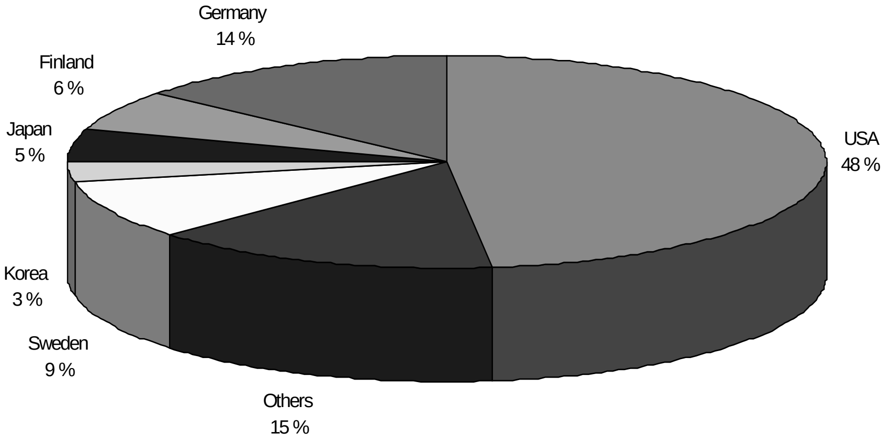


Fig. 1. Worldwide sale of CFB boilers by country. Percentages are calculated based on number of the installed units in each country (Grace *et al.* 1997).

The pioneers utilizing CFBC technology were the companies Lurgi in Germany and Ahlstrom in Finland. Both companies made their first commercial installations in the early 1980s. The main difference between the Lurgi and Ahlstrom boilers was that the Ahlstrom boiler did not use an external heat exchanger. The required heat was absorbed entirely by the furnace surfaces. The third contemporary developer was Battelle Memorial Laboratory in the U.S.A. Unlike Lurgi or Ahlstrom, Battelle used a very high gas velocity in the combustor and called it Multi Solid Boiler (Basu & Fraser 1991). Figure 2 shows the market share data during1979-1994 for the CFB boiler business.

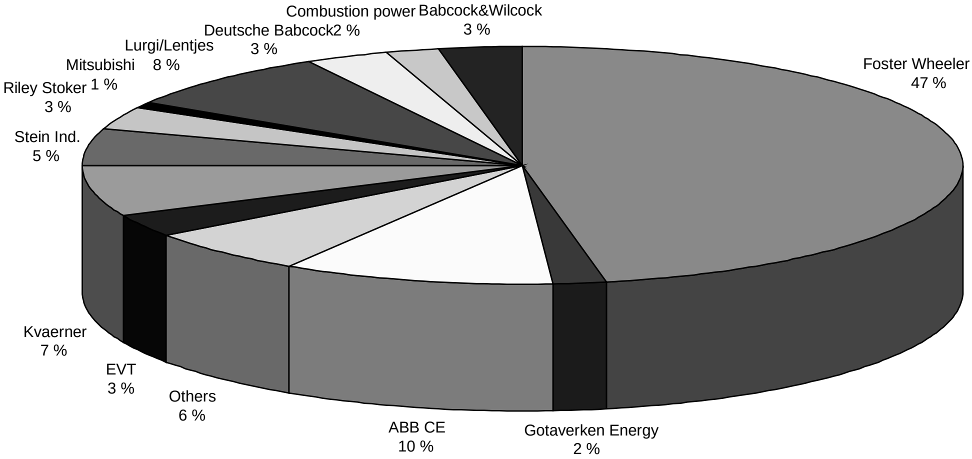


Fig. 2. CFB Market shares 1979-1994 according to the orders from the boiler constructors on the MW(e) basis (McCoy 1995).

1.2. Fuzzy logic in process control

The theory of fuzzy sets was first introduced in 1965 by Lofti Zadeh of the University of California, Berkeley (Zadeh 1965). One of the first implementations of fuzzy type of control was made in Denmark (Ostergaard 1996). They implemented a decision table based fuel control for a cement kiln in 1972. The idea of implementing a control strategy as a decision table —which basically was a rough description of the manual control scheme— was copied from the text book made for the kiln operators.

Even though the fuzzy logic control, based on the theory of fuzzy sets, was initiated more than thirty years ago, it did not gain significant interest until the last decade in the process industry. So far, the Japanese home electronic suppliers have achieved the greatest publicity. Now this situation is changing quickly. A lot of research on process control application as well as many other types of applications has been made with accelerating velocity.

Nowadays, it is common to find fuzzy applications throughout the process industry. Process control system suppliers, universities, research centers, and the process industry have implemented thousands of exciting applications. This success has not only been possible because of higher knowledge of fuzzy set theory alone but also due to the development of easier and more advanced tools for Fuzzy Logic Control (FLC) implementation.

Examples of industrial applications of fuzzy logic can be found from the following references: (Tong 1977, Sugeno 1985, Evans *et al.* 1989, Terano *et al.* 1994, Driankov *et al.* 1995, Zimmermann 1996, Bonissone *et al.* 1995, Thomas & Armstrong-Helouvry 1995, Taipale 1998, Palmu 1998, Järvensivu 1998 and Murtovaara *et al.* 1998).

1.3. The research work

The research work introduced in this thesis was made in co-operation with Varenso Oy Varkaus, Finland (the power plant), Foster Wheeler Energia Oy Karhula, Finland (the CFB manufacturer’s research center) and Honeywell-Measurex Varkaus, Finland (automation applications). The work was started during the spring of 1996 and continued through the spring of 1998 when the advanced control applications were controlling the industrial boiler successfully.

1.3.1. The scope of the research

The objective of the research was to study how FLC, neural networks, and linear optimization can solve different kinds of control problems in a multi-fuel CFB boiler. Since fuzzy logic proved to be the most suitable solution for most of the problems, fuzzy logic applications are the main topic to be addressed in this thesis. The management of abnormal situations, e.g. uncontrolled increase of the fuel inventory in the bed, were also listed as topics to be studied. In addition to the control strategy development, another important issue was to implement and test those applications in a real industrial environment.

1.3.2. Research methodology

This research work was started to aid in understanding the existing problems in daily boiler control. This was based on many discussions with boiler operators and engineers. The most important task was to try to become familiar with all of the problems the operators met in their daily practice, and especially the problems which cause the greatest impact on the boiler availability.

In the second phase of the research, there were discussions with the boiler specialists to clarify and better understand the phenomena and behavior of the circulating fluidized combustion process. Existing literature and survey papers were also used to find out what experiments and solutions have previously been made and found. The theory and applications of fuzzy logic control were also studied.

The third phase of this research work included creating application candidates for the most important control problems identified in the previous phases. The control applications were programmed using **TotalPlant®** Alcont Toolboxes, which are developed to help implement advanced solutions to process control. The applications developed were tested first by using an Alcont test program in the Alcont Design Module running on a normal IBM PC. Part of the applications were also tested using the Matlab Simulink (trademarks of Math Works Inc.) process model DDE™- linked to the inputs and outputs of the control strategies. The used process model was previously developed by Foster Wheeler.

The next phase was to test the applications on the compact pilot plant at Foster Wheeler Energia Research Center in Karhula. During these experiments, most of the applications were tested under varying conditions. In the experiments, the fuel was similar to what was normally used in the industrial boiler, Varenso K6 in Varkaus. The experiments were made by making step changes to fuel-feed, fuel quality, feed breaks, overfeeding, etc.

The final phase in this work was to implement the developed control applications on the fullscale industrial boiler, Varenso K6 in Varkaus. The applications used in Karhula were re-tuned and further developed to the industrial environment. Later on, the FLC implementations data from tests runs were recorded during several weeks of the operation. After the test runs, the applications were accepted into the continuous operation by the Varenso power plant.

1.4. Contribution

In this thesis, it is proposed and demonstrated that fuzzy logic in control and used as a fuzzy expert system is a notable tool for a control engineer to improve CFB boiler control.

Properly controlling a multi-fuel industrial boiler during unexpected load changes using continuously fluctuating bio-fuel is a very difficult challenge.

FLC is well-suited for solving non-linear control cases in an industrial fullscale CFB boiler. FLC gives better control performance than PID when non-symmetric control like steam (header) pressure is needed.

Fuzzy logic control can be used to compensate disturbances caused by process inputs, which are very difficult to measure online, like the fluctuation of the bio-fuel mix heat value.

Fuel-feed optimization procedure can be used successfully, minimizing energy costs as a component of the set-point handling of the fuel power need without risking the boiler's availability.

Fuzzy decision-making used as an expert system helps boiler operators to execute control actions by pre-processing the big data flow from the process. Fuzzy decision-making is a suitable tool in creating fuzzy software sensors for “non-measurable” process values like fast-increasing bed fuel inventory in a multi-fuel boiler.

The introduction to circulating fluidized bed process and typical conventional PID-based control solutions of CFB boilers given in this thesis are based on a literature review made by the author of this thesis. The discussed typical control challenges in multi-fuel operation were recorded by the author from the Varenso K6 boiler. The presentation of fuzzy logic control and control tools consist mostly of a review and summary, where the author was responsible for finding a compact framework for the presentation.

The ideas to the suggested improvements using fuzzy logic to the CFB boiler control were partly developed together with the researchers of the Foster Wheeler R&D Center in Karhula and partly by the author alone. The non-fuzzy ideas for similar kinds of control improvements are discussed by several authors (Ikonen 1994, Ryd 1994, Åström *et al.* 1993, Ikonen & Kotajärvi 1993, Henttonen *et al.* 1992 and Kortela *et al.* 1991). Concerning the applications introduced in this thesis, the FLC compensation of the fuel quality fluctuation and fuzzy decision-making logic for increased bed fuel inventory monitoring are the results of cooperation, the author having, however, the leading role. The fuzzy steam pressure controller and the fuel-feed optimization procedure were designed by the author.

The programming work and the implementation, as well as the tuning to the Karhula pilot plant, were made by the author. The experiment program and the experiments made in Karhula were planned and realized together with the staff of the Karhula R&D Center. The author is fully responsible for the modifications and re-tuning work needed to be made for those applications when implemented to the Varenso K6 industrial CFB boiler. The implementation work was done by the project engineers of Honeywell-Measurex. The data recording during the Karhula pilot plant experiments was done by the Foster Wheeler researchers and was analyzed by the author. During the test runs in Varenso K6 power plant, the data was recorded by the staff of the power plant and was mostly analyzed by the author with some help from Foster Wheeler researchers. The author of this thesis is fully responsible for the conclusions made based on the pilot plant experiments done in Karhula and test runs made in the Varenso K6 boiler.

1.5. Results

The results obtained after the implementation of new control applications were positive. Comparing the process values such as steam pressure, flue gas oxygen and the amount of used coal per produced steam flow before and after the new controls, clearly showed improved combustion control performance.

The most important feature of the industrial boiler, which must be noted, is the availability. Because the improved availability is rather difficult to measure reliably within a short time like two to three months, it was not relevant to introduce any exact figures.

It was discovered that fuzzy logic is a very suitable tool to solve CFB combustion control challenges. The use of fuzzy logic to not only control actions but also to create fuzzy software sensors or fuzzy expert systems should not be forgotten. A fuzzy decision-making system was developed, which combined many process inputs into one or two fuzzy values helping the operator with decision-making and control actions.

In spite of good results, the reader should remember that fuzzy logic is just one tool, one of many, to solve process management challenges, nothing more. Without proper process experience and knowledge to design and tune the applications correctly, the advanced tools like fuzzy logic do not bring any better results than conventional systems do.

1.6. Contents

This thesis contains seven chapters:

- Chapter 1 states the research problem and gives a brief introduction to its background and to the development of the CFBC- and FLC- technology.

- Chapter 2 provides an introduction to CFB boilers, multi-fuel flexibility and the role of different boilers in this work.

- Chapter 3 contains a brief overview of fuzzy logic and its theoretical background. The tools used to implement fuzzy logic applications in this work are also introduced.

- Chapter 4 introduces the conventional control solutions and the studies of the related research work, which have been done concerning use of fuzzy logic and other tools controlling CFB combustion and other types of boilers. Typical control problems in multi-fuel boilers are also discussed.

- Chapter 5 introduces the control philosophies, rule-bases and decision-making principles used in developing the suggested applications.

- Chapter 6 shows the main results of the experiments completed in the pilot plant and fullscale industrial boiler and gives the analysis and discussion of the results of this research work.

- Chapter 7 summarizes the main issues discussed in this thesis.

2. Circulating fluidized bed boiler

This chapter introduces the process of Circulating Fluidized Bed Combustion (CFBC). Some of the CFBC process phenomena and properties are discussed in more detail than others. This is not intended to be a fullscale process description. For a more detailed explanation of CFB boilers as well as the fluidization theory, see text books by Davidson & Harrison (1971), Howard (1983), Kunii & Levenspiel (1991), Basu & Fraser (1991) or Grace *et al.* (1997).

At the end of this chapter, two different CFB boilers used in the experimental part of this thesis are introduced.

2.1. The CFB combustion process

Basu and Fraser have defined the CFB boiler as follows (Basu & Fraser 1991):

> *A circulating fluidized bed (CFB) boiler is a device for generating steam by burning fossil fuels in a combustion chamber operated under a special hydrodynamic condition. Fine solids are transported through the combustion chamber at a 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 combustion chamber.*

2.1.1. Boiler description

The main components of a typical CFB boiler are shown in Fig. 3. These consist of a combustion chamber, a cyclone separator and a return leg for re-circulation of the bed particles.

The combustion chamber is enclosed with water-cooled tubes and a gas-tight membrane. The lower section of the of the combustion chamber is covered with refractory with openings for introducing fuel, limestone, secondary air, recycled ash, one or more gas or oil burners for start-up and bottom ash drains. Most of the combustion occurs in the lower section, while the heat transfer to the walls is achieved mainly by particle convection and radiation in the upper section of the combustion chamber.

The cyclone separator can be water-cooled, steam-cooled or without cooling and is designed to separate the entrained solids from hot flue gas and return them through the return leg and possible loop seal. The loop seal (not shown in Fig. 3) prevents backflow of gas from the riser up the standpipe and has no movable mechanical parts. The gas velocity employed in a CFB is usually in the range 4.5 to 6 m/s. Air is fed to the unit as primary air, secondary air, transport air for fuel and limestone feed, air to the loop seal and fluidizing air to the ash classifier. The bottom ash classifier is designed to remove larger bed particles and recycle small particles back to the combustion chamber for improved heat transfer. The operating bed temperature is usually in the range of 850-900 °C, but the in case of low grade fuels the bed temperature can even be below 800 °C. The temperature ranges around 850 °C optimizing the sulfur capture efficiency of limestone, combustion efficiency, NO_x content and agglomeration of the bed material as well. The limestone feed sizes are typically from 0 to 6 mm with mean size of 1-3 mm and from 0 to 1 mm with mean size 0.1-0.3 mm, respectively. (Grace *et al.* 1997.)

The basic boiler configuration of major CFB boiler manufacturers such as Lurgi, Kvaerner Pulping, and Foster Wheeler are similar, with the main components being the combustion chamber with water-wall, cyclone and return leg, and back-pass. The main design differences are in the external heat exchanger, grid design, and ash handling systems. The Lurgi design usually features an external heat exchanger, whereas the Foster Wheeler design has an INTREX™ internal heat exchanger. (Grace *et al.* 1997.)

Kvaerner Pulping has introduced a new design named CYMIC®, where the cyclone is located inside the combustion chamber. The cyclone is totally water-cooled, operating in natural circulation like the walls of the combustion chamber. (Kokko & Kinnunen 1998.)

Figure 3 shows a schematic diagram with the main components of the Foster Wheeler CFB boiler and Fig. 4 illustrates the design of Kvaerner Pulping, respectively. In Figure 3, the main components of a typical CFB boiler are also introduced.

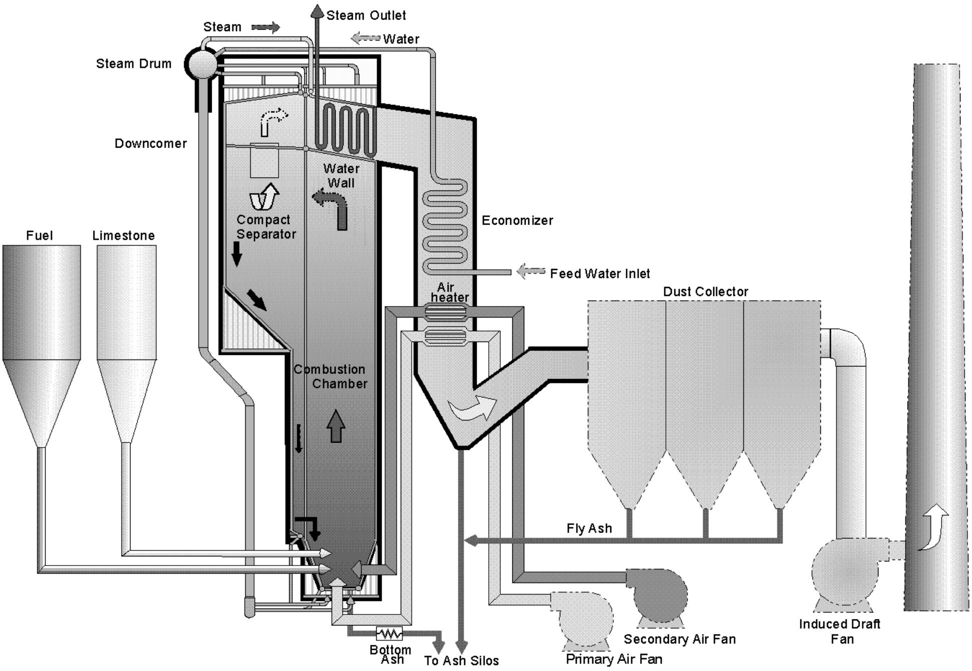


Fig. 3. Foster Wheeler's Compact CFB boiler with a square cyclone, which is a centrifugal separator joined to the combustion chamber without expansion joints. The separator is fabricated with flat walls constructed from conventional water-cooled membrane panels and covered with a thin refractory lining. (Foster Wheeler 1996.)

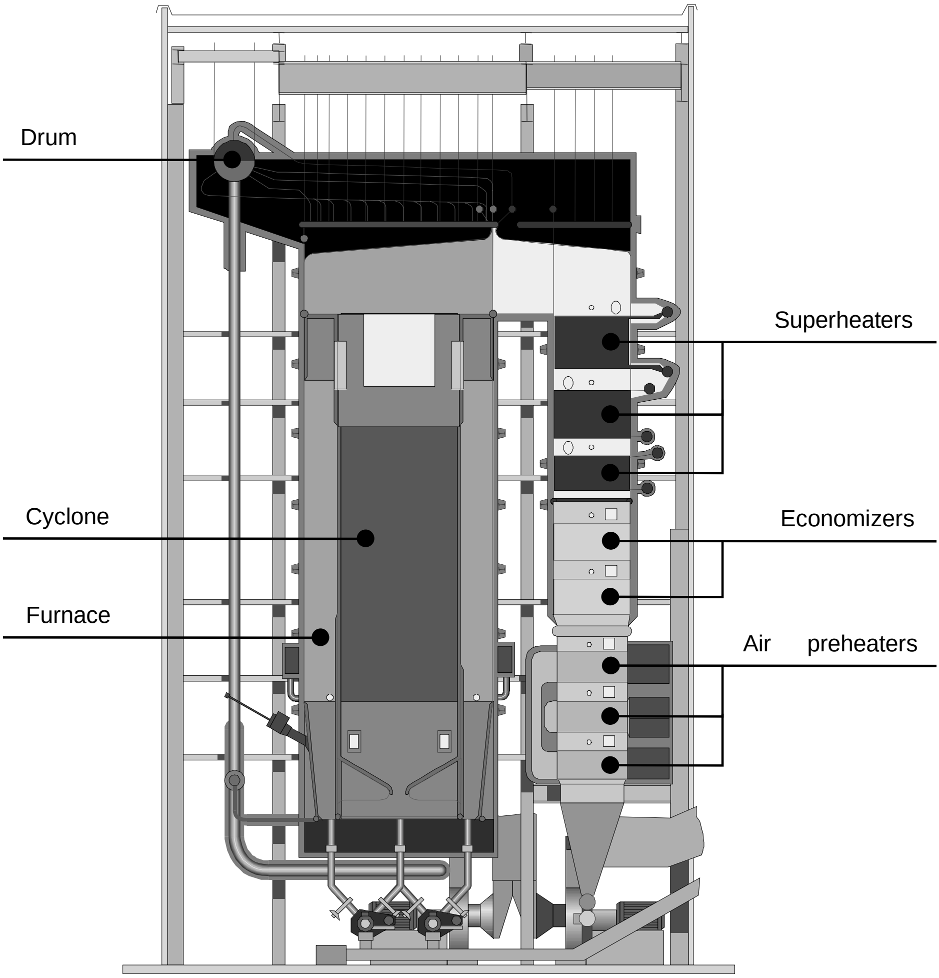


Fig. 4. Kvaerner's CYMIC® CFB boiler with round cyclone inside the combustion chamber (Kvaerner 1997).

2.1.2. Fuel-feed systems

The fuel-feed system typically includes fuel silos, gravimetric feeders, chain conveyors and screw feeders. The types of equipment used for conveying various types of fuels must be chosen carefully to ensure proper operation. Drag chain, belt and screw conveyors present different problems to different fuels. In general, belt conveyors are not as maintenance-intensive as drag chain conveyors and are especially suitable for conveying fuels that are particularly abrasive, sticky or potentially corrosive.

Figure 5 shows a typical simplified arrangement of waste fuel-feed line including fuel silo, conveyors and rotary feeders. Nowadays, the fuel-feed systems are often equipped with proper fuel pre-mixing and screening facilities.

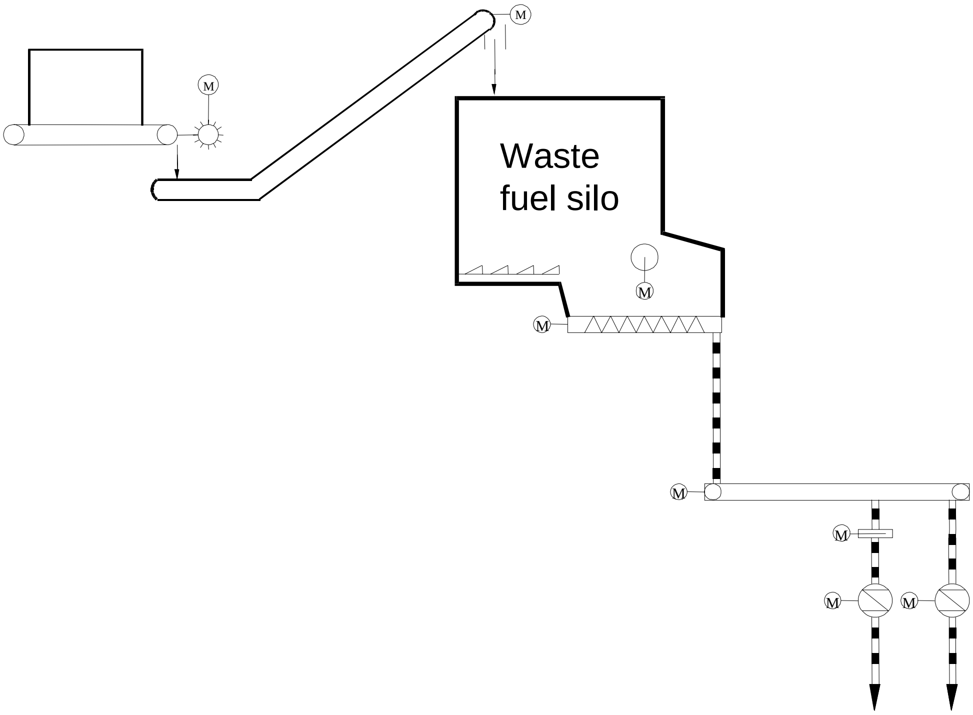


Fig. 5. A typical simplified arrangement of waste fuel-feed system in a fluidized bed boiler (Adapted from Honeywell 1994).

The amount of fuel-feed lines as well the type of fuels varies a lot among multi-fuel boilers. One typical example of fuel-feed system structure is shown in Fig. 6, which shows a fuel-feed system for two separate fuels. Fuels (coal and waste) are loaded from trucks or debarking plant into four silos. Feeding to the combustion chamber is divided into two separate lines so that one line (two silos) can fulfill the fuel power need by using coal in case of feeding problems in another line. Waste fuel and coal are mixed in conveyors before the fuel is fed through rotary feeders into the combustion chamber.

The number of fuel-feed points per unit area is determined from the fuel characteristics and the degree of lateral mixing in the specific design of the combustion chamber. The rate of fuel-feed is automatically controlled in response to the main steam header pressure. (Grace *et al.* 1997.)

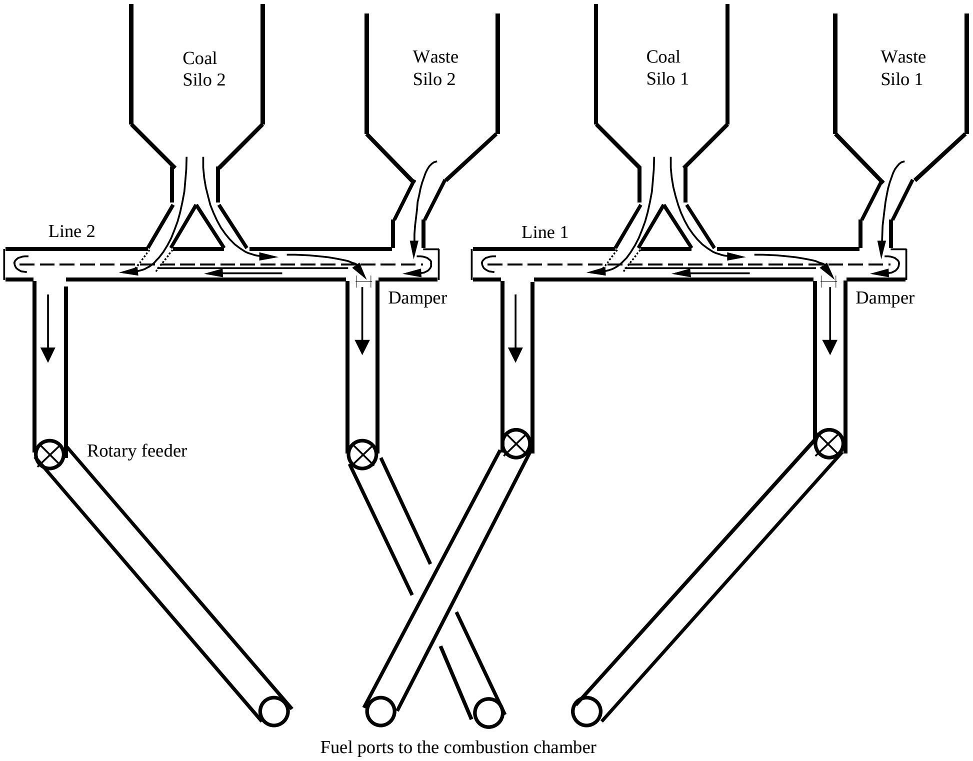


Fig. 6. A schematic diagram of the Varenso K6 CFB boiler's fuel-feed system. If the Damper (each line) is open too much, the coal is fed to both walls (left and right) of the combustion chamber and waste fuel only (mostly) to the right wall. If the Damper is closed too much, both coal and waste are fed to the left wall. If the rotary feeder stops (two per each line) the whole feed line must be stopped.

2.1.3. Fluidization

Kunii and Levenspiel have provided a definition for fluidization as follows (Kunii & Levenspiel 1991):

Fluidization is the operation by which solid particles are transformed into a fluidlike state through suspension in a gas or liquid.

The basic idea in CFB combustion is the fluidization of the bed material (normally sand mixed with fuel ash and possible sorbent material) by injecting primary fluidizing air through the bottom of the combustion chamber. The fluidizing degree depends on the velocity of the air.

Depending on the authors like Davidson & Harrison (1971), Howard (1983) and Kunii & Levenspiel (1991), the fluidization has been introduced by using various forms of contacting a batch of solids by fluid. One simplified description has been proposed by Raiko (Raiko *et al.* 1995) where the four different fluidization phases are specified as depicted in Figure 7.

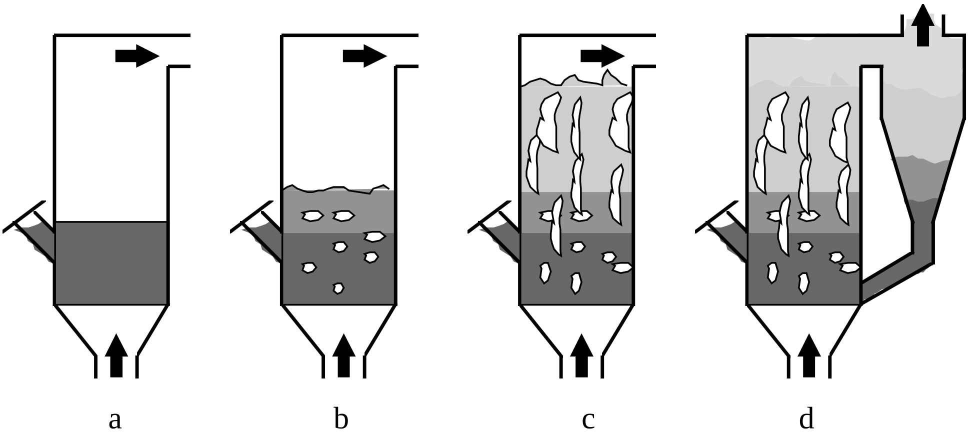


Fig. 7. Fluidization phases. When the fluidizing air or gas velocity is increased, the gas-/solid-contacting mode moves from fixed bed (a) to bubbling bed (b). If the fluidizing air velocity is further increased, the bed transforms into turbulent bed (c) and finally to circulating bed (d). (Adapted from Raiko *et al.* 1995.)

The superficial velocity at the minimum fluidizing conditions (u_{mf}) has been often introduced by using so called Ergun’s Equation (Howard 1983, Kunii & Levenspiel 1991, Raiko *et al.* 1995):

$$\frac{150(1-\varepsilon_{\mathrm{mf}})}{\varepsilon_{\mathrm{mf}}^{3}\,\phi^{2}}\,Re_{\mathrm{mf}} + \frac{1.75}{\varepsilon_{\mathrm{mf}}\,\phi}\,Re_{\mathrm{mf}}^{2} = Ar\ , \qquad (1)$$

where *Re* is Reynolds number defined:

$$Re_{\mathrm{mf}} = \frac{d_{\mathrm{p}}u_{\mathrm{mf}}\,\mathrm{g}}{\mathrm{g}}\ , \qquad (2)$$

and *Ar* is Archimedes number defined:

$$Ar = \frac{d_p^{3} \rho_g (\rho_s - \rho_g) g}{\mu_g^{2}}, \tag{3}$$

in which

ε_{mf} is void fraction in the bed [-]

ϕ is sphericity of bed solids [-]

μ_g is viscosity of gas [kg/ms]

ρ_g is density of the gas [kg/m^3]

ρ_s is density of the solid [kg/m^3]

d_p is surface-volume mean diameter of particles [m]

g is gravity constant [9.8 m/s^2].

The minimum fluidization velocity is not the operation mode of a CFB and it is worth concentrating more on fast fluidization. In the context of its use in CFB boilers, the fast fluidized bed may be defined as (Basu & Fraser 1991):

Fast fluidized bed is a high velocity gas-solid suspension where particles, elutriated by the fluidizing gas above the terminal velocity of single particles are recovered and returned to the base of the combustion chamber at a rate sufficiently high as to cause a degree of solid refluxing that will ensure a minimum level of temperature uniformity in the combustion chamber.

The terminal velocity u_t for particles can be written (Raiko *et al.* 1995):

$$u_t = \left[\frac{4}{3} d_p \frac{(s-1)}{C_D} g \right]^{1/2}, \tag{4}$$

in which

$s = \rho_s / \rho_g$,

and C_D is resistance factor depending on the Reynolds number.

Besides the velocity of the primary fluidizing air, the particle size of the bed material has an important effect on the bed fluidizing process. Naturally, the finer fraction of the bed material will be fluidized and elutriated more easily than bigger particles. When solids with a wide size distribution and different densities are fluidized, segregation of solids may occur. (Grace *et al.* 1997.)

Circulating fluidized beds exhibit very complex hydrodynamics caused by interactions between the gas and solid phase. The motions of gas and solids are driven by mechanisms that are difficult to identify and describe.

Although the gas and solids motions inside the combustion chamber are complicated and depend on separate variables, the main streams of the solids can be described by the simplified model depicted in Figure 8.

The dynamics of the multi-phase flow and fluid dynamic characteristics of circulating fluidized bed boilers have been discussed by many authors (Hyppänen 1989, Golriz 1992, 1994, Basu & Nag 1996, Kallio *et al.* 1996 and Blomster & Kojola 1996). The goal of these research projects has been to improve the accuracy of the heat transfer correlation in circulating fluidized beds and mathematical modeling of gas/solid two-phase flow in the different parts of the fluidized bed.

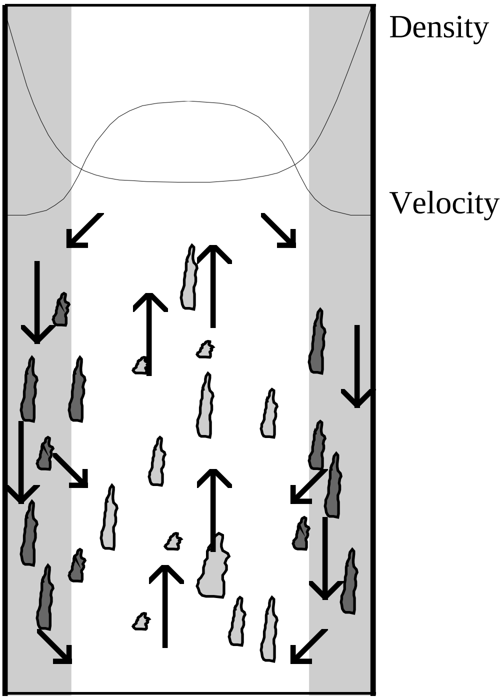


Fig. 8. Typical particle motion inside the circulating fluidized bed reactor. The solid density increases near to the walls because the gas velocity is lower. Part of the particles combine together to form particle agglomerates known as clusters. These clusters are falling downwards and form internal material circulation inside the reactor or combustion chamber. (Redrawn from Raiko *et al.* 1995.)

2.1.4. Combustion and heat transfer

A coal particle injected into a fluidized bed undergoes the following sequential events (Basu & Fraser 1991):

- Heating and drying,
- Devolatilization and volatile combustion,
- Swelling and primary fragmentation (for some types of coal),
- Combustion of char with secondary fragmentation and attrition.

These processes are shown qualitatively in Fig. 9, which shows the order of magnitude time taken by each step.

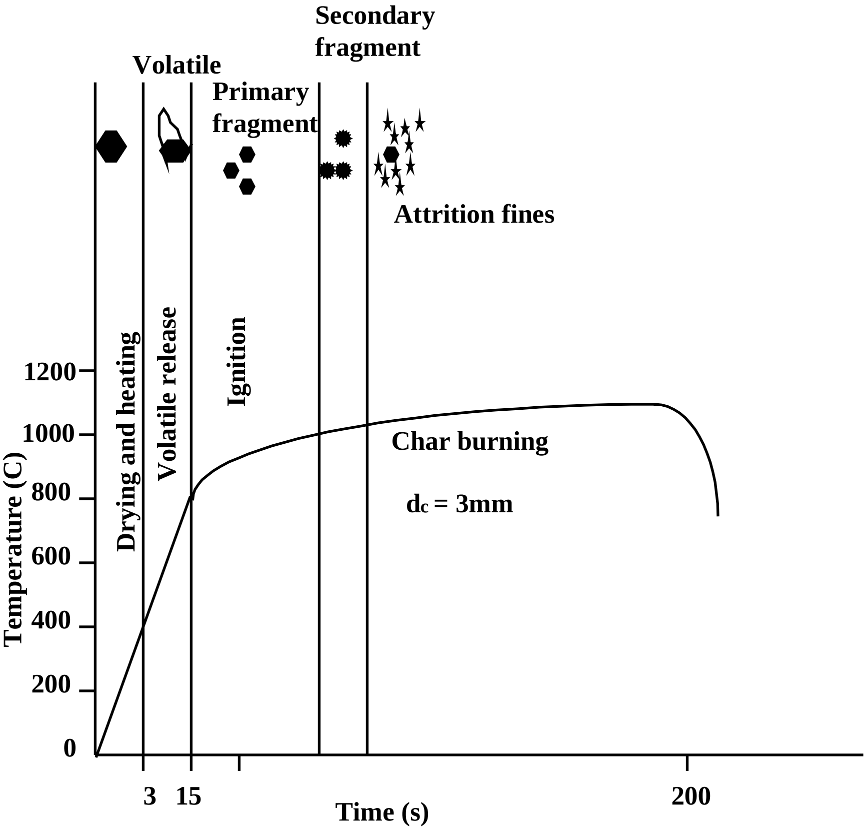


Fig. 9. The sequence of events in the combustion of a coal particle and the temperature of the char particle surface (Redrawn from Basu & Fraser 1991).

In the case of burning highly moist bio-fuel, the drying and devolatilization are the main stages of the combustion, since the fixed carbon content can only be around 10% of single particle mass. Moisture in biomass can exist in three forms: as free water in the cell cavities, as bound water absorbed on the cell walls and as vapor.

As the drying proceeds, the surface of the particle reaches a temperature at which devolatilization commences. After that, the pyrolysis front continuously progresses towards the center of the particle since the thermal wave follows the wet/dry interface. Actually, the volatiles release occurs in a finite temperature range, which makes the term “pyrolysis front” quite loose. However, based on the upper limit of the range as a conventional pyrolysis temperature, T_p (see Fig. 10), an abrupt pyrolysis can be considered to occur at the receding char/dry biomass interface for the estimate of the loss of volatiles. (Palchonok *et al.* 1997.)

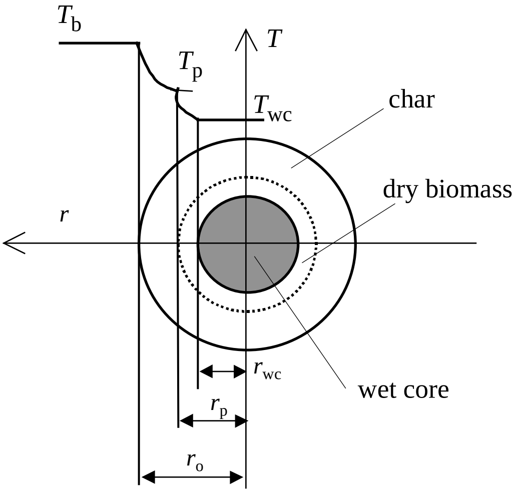


Fig. 10. Temperature distribution inside a wet sphere. T_{wc} (wet core temperature), T_p (pyrolysis temperature) and T_b (bed temperature) illustrates the temperature decrease from the surrounding bed to the wet core. The r_{wc}, r_p and r_o are the radiuses respectively. (Redrawn from Palchonok *et al.* 1997.)

The combustion of char generally starts after the evolution of volatiles; sometimes there is an overlap of the two processes. During the combustion of a char particle, oxygen from the bulk stream of the combustion chamber air is transported to the surface of the particle. The oxygen then enters into an oxidation reaction with the carbon on the char surface to produce CO_2 and CO according to the following basic equations (Basu & Fraser 1991):

$$C + O_2 = CO_2 \tag{5}$$

$$C + \tfrac{1}{2} O_2 = CO. \tag{6}$$

Heat value is the most important factor when the fuel types and fuel mixtures are classified. The fuel is said to have a gross and net heat value, which are called higher and lower heat value. The moisture content affects the lower heat value of the fuel and lower heat value can be calculated following the ISO 1928-standard (Raiko *et al.* 1995):

$$Q_{\mathrm{net,v,m}} = (Q_{\mathrm{gr,v}} - 206[H])\frac{100 - M_{\mathrm{T}}}{100 - M} - 23M_{\mathrm{T}}\,, \tag{7}$$

in which

$Q_{\mathrm{net,v,m}}$	is lower heat value in constant volume [J/g]
$Q_{\mathrm{gr,v}}$	is higher heat value in constant volume [J/g]
$[H]$	is hydrogen content of the analyzed sample [wt %]
M_{T}	is fuel moisture [wt %]
M	is moisture of analyzed sample [wt %];

For dry fuel $M_{\mathrm{T}} = 0$ and for analyze moist fuel $M_{\mathrm{T}} = M$.

In this thesis, the fuel heat value discussed means lower heat value which is also often termed as effective heat value.

The combustion chamber of the CFB boiler can be divided (Basu & Fraser 1991) into three distinct zones. The zones are the lower zone (located below the secondary air level), the upper zone (located above the secondary air level) and the hot gas/solid separator.

The lower section, fluidized by the primary air, receives fresh coal or fuel mix from the feeding system and unburned char from the hot cyclone. Devolatilization and partial combustion occur in this zone, which is usually oxygen-deficient. The secondary air is added at the interface between the lower and upper zone of the combustion chamber. Char particles, transported to the upper zone, are exposed to an oxygen rich environment, where most of the combustion occurs. Sometimes part of the combustion takes places in the cyclones which causes unnecessarily high cyclone temperatures.

In a circulating fluidized bed, heat transfer to the walls is the result of convection/conduction from particles falling along the walls, thermal radiation, and gas convection to the uncovered surface areas. The mechanism of particle convection/conduction is the process in which particles move to the heat transfer surface as a consequence of the periodic and random motions in the bed. (Golriz 1994.)

Basu and Nag state as a conclusion in their paper (Basu & Nag 1996), that the understanding of heat transfer in a circulating fluidized bed is still in a developing stage. Suspension density seems to be the most significant factor influencing the heat transfer. Other factors are the bed temperature and the vertical length of the heat exchanger. The direct effect of particle size is evident with short heat transfer surfaces but it is not significant with long surfaces similar to those used in commercial boilers.

2.1.5. Emissions

A much-studied item concerning CFB boilers is the emissions from the boiler units burning different fuels. Many authors (Asai *et al.* 1990, Edvardsson & Alliston 1993, Lyngfelt *et al.* 1995, Hiltunen & Lee 1992, Karakas & Vourliotis 1995, Basu & Fraser 1991, Raiko *et al.* 1995 and Grace *et al.* 1997) have discussed the NO_x , N_2O, CO and SO_2 emissions of the CFB boiler in their text books and conference papers. In this thesis, the emissions and emission control are not the main purpose of the discussion and more thorough discussion of these topics can be found in the sources mentioned above. However, some main features and operating parameters are presented below.

The NO_x emissions from the CFB boiler are, in general, lower than that from the bubbling fluidized bed boiler. Theoretically, the nitric oxide (NO_x) is formed through oxidation of atmospheric nitrogen and fuel-bound nitrogen. Low combustion temperature used in the CFB boiler (750-900 °C), however, inhibits the oxidation of the nitrogen of the combustion air to thermal NO_x. The generation of NO_x in a combustion system can be reduced to some degree through the following modifications (Basu & Fraser 1991) of the system:

- Lowering of combustion temperature because NO_x generation from nitrogen is also found to decrease with temperature, although the formation of thermal NO_x is negligible,
- Staging of air between different sections,
- Injection of ammonia into the upper section of the combustion chamber or cyclones,
- Low excess air.

The nitrogen content of fuel is typically 1-2 % on a dry, mineral-free basis. The nitrogen in fuel is divided between the volatiles and the char. The char nitrogen is oxidized to nitric oxide through a series of reactions. The volatile nitrogen takes part in a parallel-consecutive reaction in which NO is formed by the oxidation of the volatile nitrogen. A part of nitrogen oxide formed above is also reduced back to nitrogen. A large number of complex chemical reactions are involved in the formation and destruction of nitric oxide from both char and coal volatiles. Some of these reactions are catalyzed by calcined limestone (CaO), spent limestone ($CaSO_4$) and char. (Basu & Fraser 1991.)

If the fuel contains sulfur, it can be captured by adding a sorbent (normally limestone) to the combustion chamber. The reduction in SO_2 emission from the CFB boiler and the extent of utilization of sorbents are effected by a number of design and operating parameters (Basu & Fraser 1991), which include:

- Combustion temperature because the reactivity increases with temperature, reaching an optimum value around 800-850 °C and then it drops,
- Circulation rate and bed density because at higher bed densities the average extent of sulfation increases, which tends to reduce the sulfur capture rate,
- Gas residence time/height of the combustion chamber because sulfur capture in a CFB boiler takes place mainly above the secondary air level of the combustion chamber,
- Solid residence time because the sulfation of the sorbents is a relatively slow process,

- Pressure of the combustion chamber because the equilibrium temperature for calcination of limestone decreases with decreasing pressure,
- Pore characteristics because a good reactive sorbent must have a proper balance between large pores and fine pores ,
- Sorbent size because finer sorbents leave a relatively small unreacted core after sulfation, although it can not be too fine.

Emissions of hydrocarbons and carbon monoxide (CO) from combustion systems represent losses in the thermal efficiency of the system. At high concentrations they also represent potentially harmful environmental releases. CO emissions are a complex function of fuel reactivity, fuel distribution, gas mixing and the thermal history of the gas as it passes through the combustion chamber. For homogeneous fuels, there is relatively little deviation of the instantaneous CO value from the average. However, with non-homogeneous fuels such as waste, it may be difficult to ensure feed consistency. In these cases, CO spikes and transient phenomena may account for a large portion of CO emission. (Grace *et al.* 1997.)

Emission control is, nowadays, attaining a more and more important role in CFB boiler control as well. Because the emissions are strongly dependent on process conditions, it is important to find optimal values for process values with respect to emissions. A complete optimization (Edvardsson & Alliston 1993) of N_2O, NO_x, SO_2, and CO, all at the same time, will result in the operation of the CFB boiler at increased combustor temperature of about 900 °C, and at decreased excess air of 15-20 %. The main reason for the high temperature is to decrease N_2O emissions and to achieve decreased CO and increased combustion efficiency at low excess air levels. On the other hand, a high bed temperature will have a negative effect on NO_x increase. The reason for low excess air levels is to decrease NO_x and N_2O emissions. The lower limit for excess air is determined by the acceptable CO emission and combustion efficiency.

In general, the optimization (minimization) environment of emissions differs from boiler to boiler. The limiting factor varies based on local pollution restrictions and fuels available. For example, the need of SO_2 control highly depends on used fuels.

2.2. Multi-fuel flexibility

One of the generally agreed advantages in fluidized bed combustion is the ability to utilize different kinds of fuels and even wastes. In this thesis, the fuel flexibility of the CFB boiler is discussed.

Many authors (Makansi 1997, Alliston *et al.* 1995, McGowing & Howe 1992, Grace *et al.* 1997, Ohme *et al.* 1991, Saxena & Jotshi 1994 and Martin 1991) have introduced long lists of suitable and tested fuels for the CFB boiler. Typically those lists include fuels as follows:

- Coal and brown coal,
- Anthracite,
- High ash coal,

- Sod and milled peat,
- Wood and wood waste,
- Petroleum coke,
- Paper waste,
- Agriculture waste,
- Bark,
- Gases,
- Differing sludge,
- Residual and waste oils,
- Oil shale,
- Shredded tires,
- Classified residues,
- Plastics.

The main reason the CFB boiler is capable of using various fuels and low grade fuel mixes is due to the large amount of heat stored in the circulating bed material and ash at high temperatures. The heat stored with turbulent continuous mixing makes it possible to dry, ignite, and burn fuels that contain no less than 60 to 70 % moisture (Ohme *et al.* 1991).

One important argument for the utilization of the fuel flexibility is that the CFB boiler has environmental advantages over other boiler designs. The CFB boiler inherently produces low NO_x emissions due to lower operating temperatures and staged combustion. SO_2 can be captured *in situ* in the combustion chamber by adding sorbents such as limestone. For fuels with a high alkali metal oxide content in the ash, the inherent sulfur capture may be sufficient for the sulfur retention requirement and no addition of limestone is necessary. In addition, due to the relatively low operating temperature and the addition of limestone to the combustion chamber, heavy metals emissions from CFB units are less than those from pulverized coal boilers. For some low grade fuels that contain high amounts of chlorine and fluorine, excess lime from the combustion chamber has also been found to be effective in capturing the HCl and HF emitted during combustion in the cooled section of the boiler and in the bag-house. (Grace *et al.* 1997.)

McGowing & Howe have pointed out (McGowing & Howe 1992) the potential and growing business opportunity to utilize the good properties and the ability of the Fluidized Bed Combustion (FBC) to fire alternate fuels derived from the growing volume of municipal, commercial and industrial solid waste residues. Co-firing alternate fuels with coal or other fuels can provide economic and environmental benefits like reduced emissions and coal consumption or savings in disposal of wastes.

The wide fuel assortment can also cause problems and even damage to the boiler. For example, municipal residue contents quite often contain metals like aluminium, which melts in the normal combustion temperature and will be conveyed to the superheaters. If the amount of combusted aluminium is large, the accumulation to the superheaters can choke up the boiler. Industrial residues might include alkaline and if the alkaline content in the bed increases too much, it will influence the potential for agglomeration of the bed material.

When the content of the fuel mix continuously changes, the combustion performance inside the combustion chamber also changes. Certain fuels, like coal, burn at the lower part of the combustion chamber, while some light dry fuels, like cutter chips or finer particles of peat, rise easily to the top of the chamber.

From the point of view of boiler control, the multi-fuel combustion is very challenging. Depending on fuel pre-mixing possibilities, the combustion process needs to adapt for more or less varying fuel quality. The number of fuel-feed lines defines what kind of fuel usage optimization can be made based on energy price or emission minimization. Typically, the low grade fuel alone does not fulfill the power need or is unable to maintain proper combustion temperature and extra support fuel is needed. Most often, the support fuel used is coal, gas or oil. The nature of multi-fuel combustion and existing control challenges are discussed later on (Chapter 4) in this thesis.

2.3. CFB test units

The experimental part of this thesis was completed utilizing two different boilers. The first boiler, introduced below, is the compact pilot plant in Karhula in the Foster Wheeler Research Center where the suggested application solutions were tested. The other boiler is the fullscale industrial boiler Varenso K6 in Varkaus, where the fuzzy applications were implemented and further developed.

2.3.1. Compact pilot plant (PF650) in the Karhula Foster Wheeler R&D Center

The combustion chamber (see Fig. 11) is refractory-lined and 13.4 m high. The internal cross section of the combustion chamber is 650 mm. Primary air is supplied to the combustion chamber through a bed support plate. Secondary combustion air can be introduced at four levels in the combustion chamber freeboard place through two diametrically opposed air nozzles on each level.

The combustion chamber is equipped with a gas burner for the start-up. Depending on the fuel quality, the solid fuel-feed is started when the combustion chamber temperature reaches 600-800 °C. The solid fuel is fed into the combustion chamber as well as the limestone for SO_2 absorption, if necessary.

High superficial air velocity causes entrainment of fine bed material from the dense bed region into the combustion chamber freeboard space. Heat is removed from the combustion chamber by water-cooled Omega panels and with piston bayonet coolers inserted in the circulation downcomer.

Bed ash is removed through the ash cooler and ash is conveyed to the ash disposal system. Temperatures and pressures are measured at numerous points within the combustion chamber. Ash may be recycled to the combustion chamber from the multi-cyclone via a pneumatic delivery system. The ash re-circulation rate can be adjusted from the control room.

A refractory-lined separator (cyclone) is used to separate the suspended solids from the flue gases. The cyclone operates at a high temperature (up to reactor temperature) and allows additional burning time for elutriated fuel particles.

At the base of the cyclone, a vertical tube delivers the solid material to a non-mechanical INTREX™ chamber. The INTREX™ chamber system is designed to allow the ash to flow back to the combustion chamber, while locking the flow of combustion gases and bed material into the base of the cyclone.

The gases exiting the cyclone, at the temperature of 800-950 °C, enters a gas/water heat exchanger (boiler) with water tubes aligned perpendicularly to the gas flow. Pressurized water (up to 12 bars) is circulated through the tubes to cool the gas to 150-220 °C. Water flows and temperatures are measured and recorded.

The boiler is equipped with shot cleaning. Dropping shots clean the heat transfer surface and, from the bottom of the boiler, the shots are transferred pneumatically back to the top. Possible tube deposits and ash are carried with flue gases into the multi-cyclone.

A multi-cyclone is located after the boiler. From the multi-cyclone, ash falls through a rotary valve into a weighed ash silo. Separated ash may be directed into a weighed silo, or into a screw feeder for pneumatic transport back to the combustion chamber.

A bag-house with air pulse cleaning removes the fine particles to an acceptable level for stack discharge. The normal operating temperature is 150-220 °C. Ash falls into a hopper in the base of the bag-house and is removed into a weighed ash silo. A valved sample line permits the collection of ash samples for analysis. During the start-up, when the gas temperature is low and near dew-point, the bag-house is bypassed.

Temperatures, pressures, flows, weights, etc. are measured and displayed in the control room. All functions can be controlled from the central control room. The plant is equipped with a sophisticated control system (Alcont 1) with a complete process control and data display. The system is in the central control room and has the main interface hardware for controlling and monitoring the entire scope of the combustion facility. The new control solutions are located in **TotalPlant®** Alcont process control system, which is integrated with the older Alcont 1 system.

Pollutants such as NO_x, SO_2 and CO are monitored continuously at the gas outlet stack during the testing. O_2 is also monitored in a continuous manner to ensure optimum test conditions.

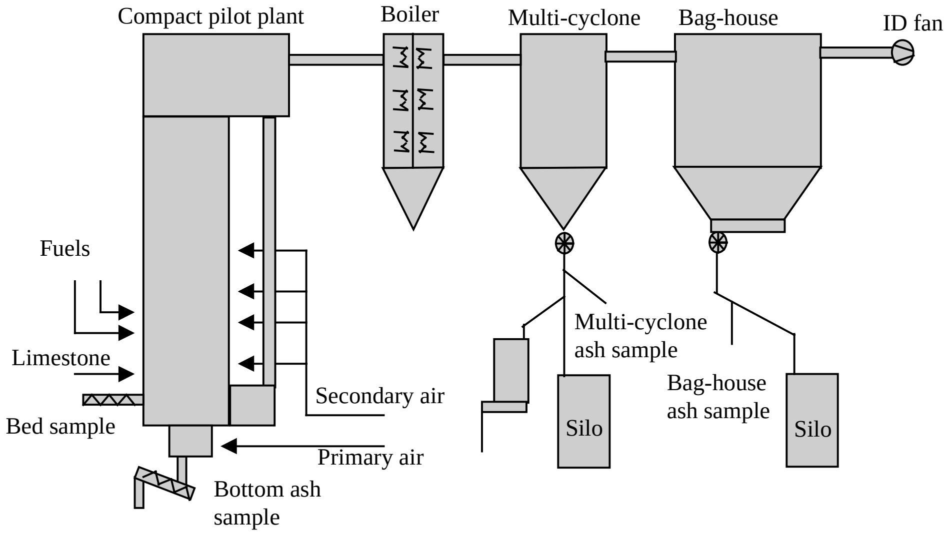


Fig. 11. Compact pilot plant at Foster Wheeler Research Center.

2.3.2. The industrial boiler K6 in Varenso Varkaus Power Plant

The boiler (see Fig. 12) is a Pyroflow®-type (now offered by Foster Wheeler) atmospheric Circulating Fluidized Bed (CFB) boiler with two cyclones. The maximum steam rate is 60 kg/s steam at 113 bar (max) pressure which means 150 MW(th) capacity. The combustion chamber is 22 m high, 10.6 m wide and 5.5 m deep and the cross section area is 58.3 m^2. Primary fluidizing air is introduced to the lower part of the combustion chamber through the fluidizing grid. Secondary air can be introduced from three different levels.

The combustion chamber is equipped with oil burners and bed lances which are used during the start-up, and also in emergency situations. The solid fuels are fed by two separate feeding lines (see Fig. 6) through a non-mechanical loop seal and are fed via four fuel ports to the combustion chamber. For both separate feeding lines, it is possible to feed either coal or waste fuel or both simultaneously.

The cyclones are located outside the combustion chamber. They are hot cyclones whose main purpose is to take care of the gas/solid separation. The outlet of the cyclones goes to the back-pass of the boiler and the bed particles are recirculated to the combustion chamber.

The combustion chamber is enclosed with water-cooled tubes and a gas-tight membrane. The lowest part of the combustion chamber is refractory-lined. The boiler has four superheaters. The second superheater is an Omega superheater and is located in the combustion chamber. The other superheaters are located in the back-pass as well as the economizer and air preheater.

The flue gas goes through the back-pass to the electrostatic precipitator and, finally, flue gases are blown to the stack. Ash is removed from the bottom of the combustion chamber by the ash-drain system. The lime feeding system is used when sulfur capture is needed.

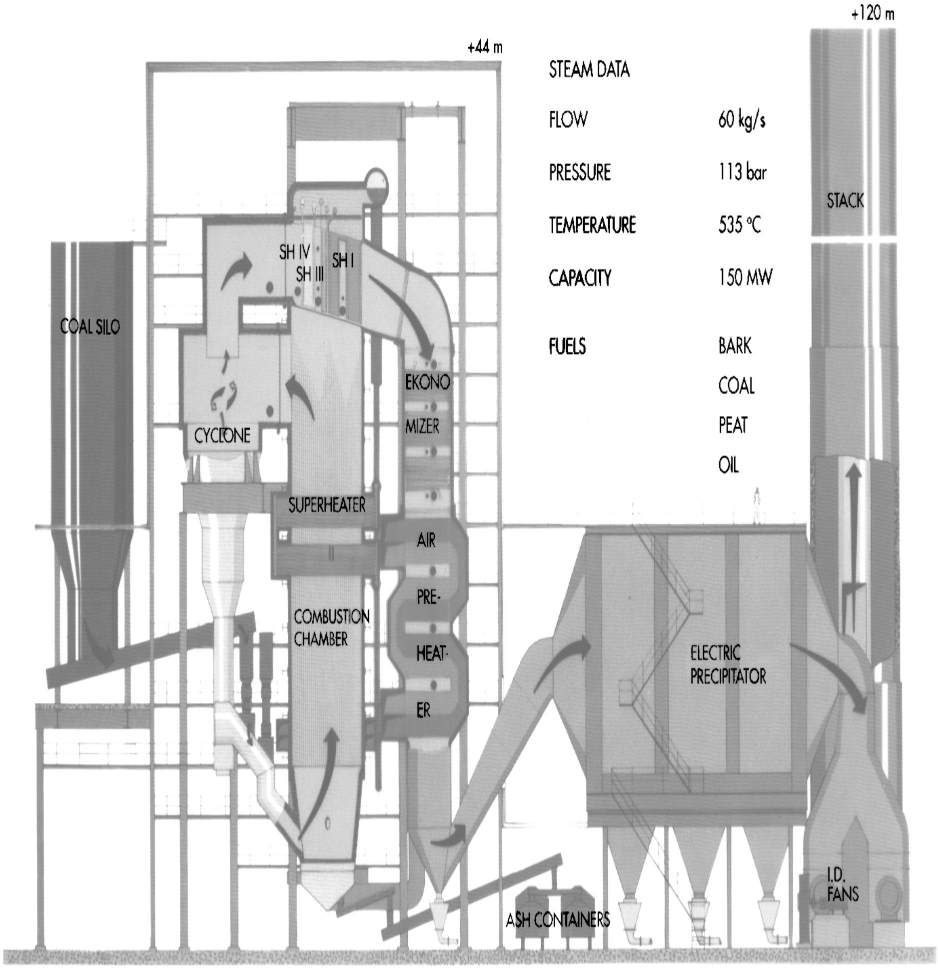


Fig. 12. Varenso atmospheric circulating fluidized bed boiler K6.

The plant is equipped with a distributed control system Alcont 1 with complete process control and data displays. The new advanced control solutions are located in **TotalPlant®** Alcont process control system, which is integrated with the older Alcont 1 system.

Fuels burned in K6 boilers vary greatly. Normally, the main fuel is spruce bark, pine bark or birch bark. Into the bark flow are typically mixed sawdust, many kinds of sludge and rejects (plastics). During the winter, sod peat has occasionally been burned depending on the sufficiency of the bark.

3. Fuzzy control and tools

Fuzzy logic controller usually refers to a fuzzy system including fuzzifier and defuzzifier according to Fig. 13. The fuzzifier maps crisp points in U to fuzzy sets in U, and the defuzzifier maps fuzzy sets in V to crisp points in V (Wang 1994). This systems brings many advantages: its inputs are real-valued variables, it makes it possible to handle if–then rules and there is much freedom in choosing mathematical descriptions for fuzzifier, inference engine and defuzzifier. The following text gives a short overview of these presentations. More details are found in numerous text books in this area (Zimmermann 1991, Driankov *et al*. 1995, Pedrycz 1993, and Wang 1994). Mathematical denotation follows the one given by Wang.

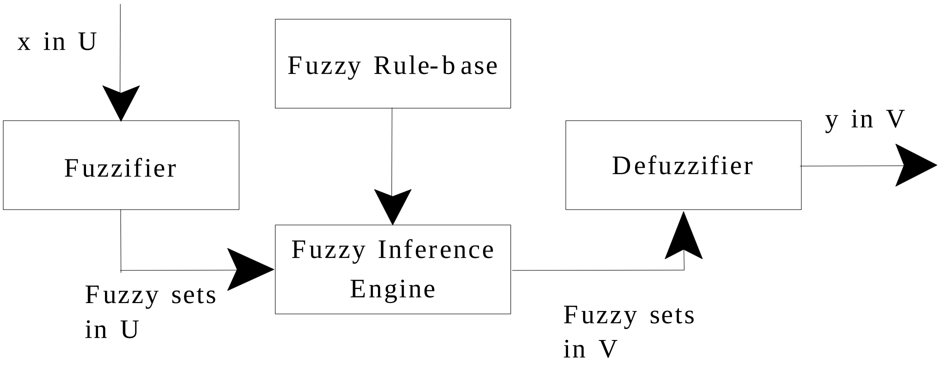


Fig. 13. The basic configuration of the fuzzy logic controller (Wang 1994).

3.1. Fuzzy sets, operations and decision-making

In conventional set theory, elements either belong fully or do not belong at all to a given set; the set membership being a logic value 1 or 0. In the fuzzy set theory, the set membership is a continuous real value between 0 and 1, describing the degree to which the element fulfills the measures of a full membership. In the fuzzy set theory, the characteristic function used in defining fuzzy set memberships is called a membership function. The membership function assigns to every $u \in U$ a value from the unit interval [0,1]. U is a collection of objects, for example, $U=R^n$ and it is called the universe of discourse. The membership function μ_F of a fuzzy set F is a function

$$\mu_F : U \rightarrow [0,1]. \tag{8}$$

The typical choices for the shape of the membership functions are triangular-, trapezoidal-, and bell-shaped. The most popular choice is the triangular-shaped function because it is the most economic one. (Driankov *et al.* 1995). Mathematical descriptions for different membership functions are given, for example, in Driankov *et al.* (1995).

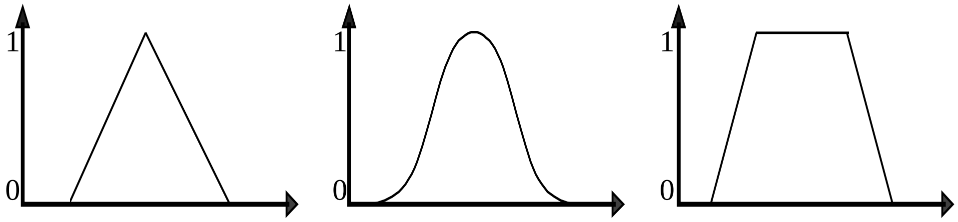


Fig. 14. Triangular-, trapezoidal- and bell-shaped membership functions.

In the fuzzification, the process value on the horizontal axis is mapped onto the membership value on the vertical axis. Typically, the process value is given by one or two non-zero membership values, because the membership functions are overlapping according to Figure 15.

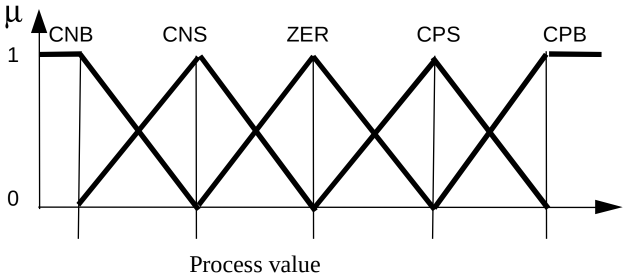


Fig. 15. A typical configuration of membership functions for a process variable.

Basic operations, intersection, union and complement, are defined also for fuzzy sets. These operations can be realized using different interpretations; the most usual being the so-called t-norm. For example, Wang (Wang 1994) describes them in detail.

The control engineer defines the behavior of the fuzzy control strategy by setting up a rule-base. The rule-base represents, in a structured way, the control policy of an experienced process operator and control engineer. The fuzzy rule-base consists of a collection of fuzzy if–then rules in the following form (Wang 1994):

$$\mathrm{R}^{(l)}:\ \text{IF}\ \ x_1\ \ \text{is}\ \ \mathrm{F}_1^l\ \ \text{and...}\ \ x_n\ \ \text{is}\ \ \mathrm{F}_n^l\ \ \text{THEN}\ \ y\ \ \text{is}\ \ \mathrm{G}^l\ , \tag{9}$$

where F and G are fuzzy sets in $U_i \subset R$ and $V \subset R$, respectively. Variables x and y are linguistic values describing the inputs and output of the fuzzy system. M is the number of fuzzy rules in the rule-base, which means that l=1, 2,…, M.

Fuzzy if–then rules are interpreted as fuzzy implications in U×V

$$\mathrm{F}_1^l \times \ldots \times \mathrm{F}_n^l \rightarrow \mathrm{G}^l\ . \tag{10}$$

If the input is given by a fuzzy set A` in U, each fuzzy if–then rule determines a fuzzy set B^l in V using the sup-star composition (Wang 1994):

$$\mu_{\mathrm{B}^l}(y) = \sup_{\underline{x}\in U}\left[\mu_{\mathrm{F}_1^l\times..\times\mathrm{F}_n^l\rightarrow\mathrm{G}^l}(\underline{x},y) * \mu_{\mathrm{A}'}(\underline{x})\right]\ . \tag{11}$$

Once again, there are several possibilities to interpret the implication in the foregoing equation. Mini-operation rule and product-operation rules are the most common. They, together with several other operation rules, are given, for example, in Wang (Wang 1994).

The output from the above equation is fuzzy. For the control use, the defuzzifier performs mapping from fuzzy sets in V to a crisp point $y \in V$. Here, several possibilities also exist: center average defuzzifier being the most common. Using the same denotations as in the previous equations, it is given as:

$$y = \frac{\mathop{}\limits_{l=1}^{M} \bar{y}^{l} (\mu_{B'}(\bar{y}^{l}))}{\mathop{}\limits_{l=1}^{M} (\mu_{B'}(\bar{y}^{l}))}, \tag{12}$$

where $\bar{y}^{l}$ is the center of the fuzzy set.

3.2. Fuzzy PI controller's scaling factors compared with parameters of the conventional linear PI controller

A conventional PI controller in discrete time is written as:

$$\begin{aligned} u(k+1) &= u(k) + \Delta u(k) \\ \Delta u(k) &= K_{\mathrm{P}} \Delta e(k) + K_{\mathrm{I}} e(k), \end{aligned} \tag{13}$$

where

$$\begin{aligned} e(k) &= y_{\mathrm{sp}} - y(k) \quad \text{and} \\ \Delta e(k) &= e(k) - e(k-1). \end{aligned} \tag{14}$$

In the equations above, the $u(k)$ is the control output and $\Delta u(k)$ is the change of control output. K_{P} and K_{I} are tuning parameters of the PI controller and the control cycle T_{s} is included into the K_{I}-term.

The fuzzy PI controller is typically written as follows (Driankov *et al*. 1995):

$$\mathrm{R}_{\mathrm{PI}}^{(i)}: \text{If } DE \text{ is LE1}^{(i)} \text{ and } E \text{ is LE2}^{(i)} \text{ then } U \text{ is LE3}^{(i)}, \tag{15}$$

where LE1$^{(i)}$…3$^{(i)}$ are linguistic values and

$$\begin{aligned} E &= N_e e, \\ DE &= N_{\Delta e} \Delta e \quad \text{and} \\ \Delta u &= N_u U. \end{aligned} \tag{16}$$

A graphical representation of the fuzzy controller defined in Equation (15) is shown in Fig. 16. It also shows the role of the scaling factors N_e, $N_{\Delta e}$ and N_u used in Equation (16).

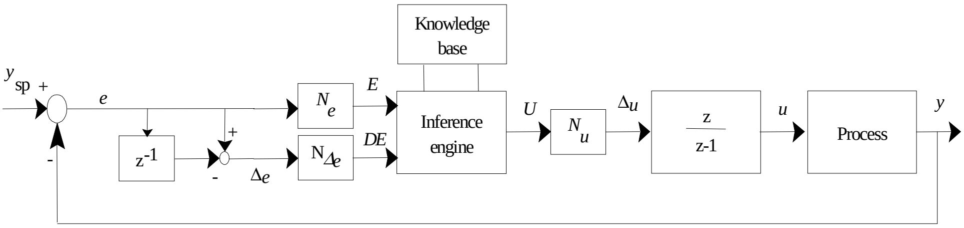


Fig. 16. A block diagram of a fuzzy controller.

Assume that the two input variables are fuzzified by using triangular membership functions depicted in Fig. 17. They consist of five fuzzy variables which are located at even intervals. The variables are quantized as depicted by integers -2, -1, 0, 1, 2.

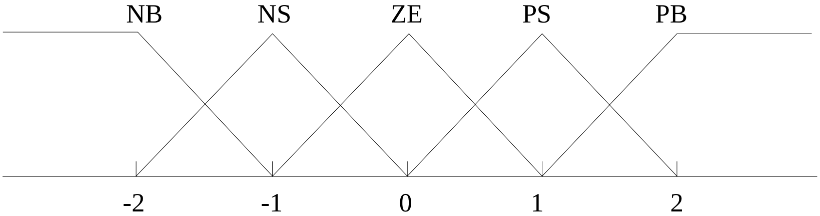


Fig. 17. The membership functions of the fuzzy variables.

Table 1 shows the complete rule-base formed by using the quantized variables. The rule-base realizes the fuzzy controller depicted in Fig. 17 and condition:

$$U = E + DE \ . \tag{17}$$

Table 1. The output values of the quantized controller.

E/DE	-2	-1	0	1	2
-2	-4	-3	-2	-1	0
-1	-3	-2	-1	0	1
0	-2	-1	0	1	2
1	-1	0	1	2	3
2	0	1	2	3	4

This can be returned back to linguistic values by agreeing into how many linguistic groups the control outputs will be classified. According to Table 1, there can be from three up to nine different classes. Assuming that the output uses the same membership functions as inputs the classification will result in five groups. By setting the values -4 and -3 as being linguistic variable NB, -2 and -1 as being linguistic variable NS, 0 being ZE, 1 and 2 being PS and 3 and 4 being PB. Then the rule-base can be written as follows:

Table 2. The output values of the controller as linguistic values.

E/DE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PB	NS	ZE	PS	PS	PB
PS	ZE	PS	PS	PB	PB

From Equations (16) and (17) it follows that:

$$\frac{\Delta u}{N_u} = N_e e + N_{\Delta e} \Delta e. \tag{18}$$

Assume that Δu corresponds to the change of the PI controller's output, the previous equation can be written based on Equation (13):

$$\frac{K_\mathrm{P}\Delta e + K_\mathrm{I} e}{N_u} = N_e e + N_{\Delta e}\Delta e. \tag{19}$$

Now by comparing the coefficients of e and Δe, the dependency between the parameters of the conventional PI controller and the scaling factors of the fuzzy PI controller can be obtained:

$$\begin{aligned} K_\mathrm{P} &= N_u N_{\Delta e} \\ K_\mathrm{I} &= N_u N_e. \end{aligned} \tag{20}$$

This means that by fixing one scaling factor, two other scaling factors for the fuzzy PI controller can be computed from Equation (20) if the tuning parameters of the corresponding conventional PI controller are known.

The presented relation is valid only in the case of linear values in Table 1. Generally, this kind of relation is difficult to derive.

Starting from the existing rule-base, it is possible to derive limits for the fuzzy controller's scaling factors if the PI controller's parameters are known. This method is suitable for the tradition of the fuzzy control because, generally, it is assumed that the fuzzy controller is constructed based on process expertise.

Assuming that the membership functions used for fuzzification and defuzzification are as depicted in Fig. 17, and having a controller as shown in Table 3, the input and output variables can be quantized into the form written in Table 4.

Table 3. A rule-base of a fuzzy PI controller.

E/DE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PB	NS	ZE	PS	PB	PB
PS	ZE	PS	PS	PB	PB

Table 4. The quantized output values of the controller.

E/DE	-2	-1	0	1	2
-2	-2	-2	-1	-1	0
-1	-2	-2	-1	0	1
0	-1	-1	0	1	1
1	-1	0	1	2	2
2	0	1	1	2	2

According to Table 4, the inputs and outputs of the controller fulfill the following conditions:

$$\frac{E+DE}{2} \le U \le E+DE. \tag{21}$$

After substituting Equation (16) into Equation (21) the following can be obtained:

$$\frac{N_u(N_e e + N_{\Delta e}\Delta e)}{2} \le \Delta u \le N_u(N_e e + N_{\Delta e}\Delta e). \tag{22}$$

Further, after substituting the Δu from Equation (13) into Equation (22), the following can be obtained:

$$\frac{N_u(N_e e + N_{\Delta e}\Delta e)}{2} \le K_{\mathrm{P}}\Delta e + K_{\mathrm{I}} e \le N_u(N_e e + N_{\Delta e}\Delta e). \tag{23}$$

Thus the upper and lower limits for scaling factors of a fuzzy PI controller can be written as a function of conventional PI controller:

$$\begin{aligned} K_{\mathrm{P}} &\le N_u N_{\Delta e} \le 2K_{\mathrm{P}} \\ K_{\mathrm{I}} &\le N_u N_e \le 2K_{\mathrm{I}}. \end{aligned} \tag{24}$$

By fixing the value for one scaling factor, the two other scaling factors can be computed from Equation (24).

3.3. Tuning and design of FLC

The FLC includes several tunable parameters. Some of the easiest parameters to modify are the scaling factors. The scaling factors either before the fuzzification or after defuzzification allow the definition of normalized base variables of the corresponding linguistic variables, and play a role similar to the gain in conventional control. (Zimmermann 1996.)

Another tuning possibility is to change the shape of the membership functions. Typically, the changes are made to the left or right width as well as to the peak value (see Fig. 15) of the membership function. The left and right width of the membership function is the first value of the base variable on the left or right side of the peak value, respectively, that has a zero membership. A membership function is symmetric if the left and right widths are equal. (Zimmermann 1996.)

The control engineer’s knowledge about the process being controlled is stored as rules in the knowledge base. The rules have a basic influence on the closed loop behavior of the system and should therefore be defined thoroughly. According to Zimmermann (Zimmermann 1996), Sugeno and Nishida have introduced four ways to find fuzzy rules. The three latest sources have been added by Zimmermann.

- The operator’s experience,
- The control engineer’s knowledge,
- Fuzzy modeling of the operator’s control actions,
- Fuzzy modeling of the process,
- Crisp modeling of the process,
- Heuristic design rules,
- Online adaptation of the rules.

The experimental tuning of the FLC is considered to be possible because the influence of the tuning parameter is local. This means that although the number of the parameters is big, each of them causes changes on only a very limited area of the control surface. (Viljamaa 1996.)

3.4. TotalPlant® Alcont Toolboxes

TotalPlant® Alcont Toolboxes are a library of type blocks that the control engineer can use for building control strategies based on fuzzy logic and many other advanced control structures.

In the Alcont DCS-system, the approach is to use the top-down decomposition by hierarchical block building. The control engineer can use the same engineering environment to create advanced controls using fuzzy logic as easily as any other type of control or logic. This allows for the use combinations of advanced technologies with each other and with other techniques. (Nieminen 1997.)

In the Fuzzy Control Toolbox, the triangular membership functions are used for fuzzification with tuning variables associated with their top-corner x coordinates. X-axis intersection points also follow the tuning variables. The result is that two memberships at a time can be non-zero and the sum of all memberships is always one. The fuzzification block allows three or five membership inputs. All input and output pins are real numbers.

For the rule-base operation, one can use “fuzzy AND” and “fuzzy OR” operators, which in this case means MIN and MAX functions. Arithmetic product as well as the average-operators are available by utilizing the basic block library. Using a graphically-shown rule-base rather than literal rules typical of conventional fuzzy logic tools makes the Alcont transparent approach to fuzzy control especially easy for the engineer; and to test and maintain for an experienced Alcont user.

The two output defuzzification blocks (Fig. 18) have either three or five membership inputs. The required tuning variables are also available. The duty function of the defuzzification blocks is to resolve an output crisp numeric value. Associated with each degree of membership input, there is a weight bar of height 1 at the x-axis position defined by the corresponding tuning variable. The height of each weight bar is scaled by the value of the associated membership input as shown with the broad-line parts of the bars. The crisp numeric output value is the x-axis projection of the mass centre of the scaled bars.

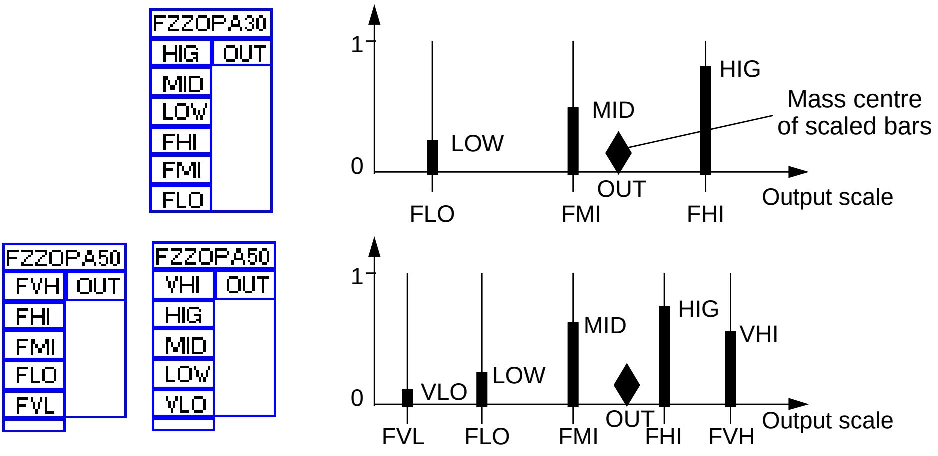


Fig. 18. Defuzzification program blocks used in Total Plant® Alcont Fuzzy Toolbox (Honeywell 1996).

3.5. Application of fuzzy systems in control

Fuzzy Logic Control (FLC) can take different forms in a common feedback control loop. The most popular ways (see Fig. 19) to use FLC are to implement a direct fuzzy controller to the process (Case a); to improve existing PID control (Case b); to make correction to the PID controller (Case c); supply the PID tuning parameters from the FLC (Case d), or finally give the remote set-point from a higher level to the PID controller (Isomursu 1995).

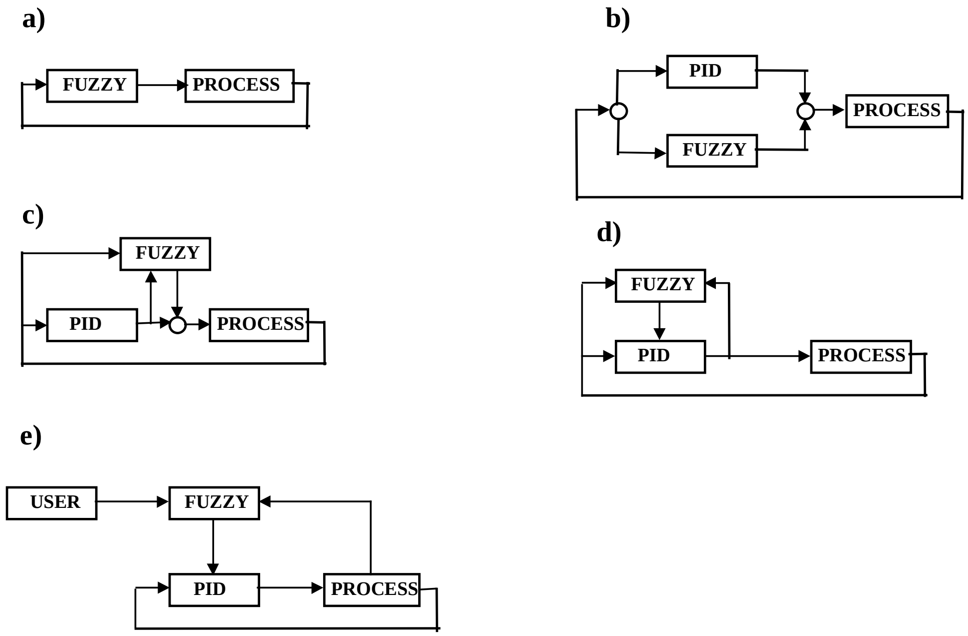


Fig. 19. The usage of FLC in different roles (Redrawn from Isomursu 1995).

It is also very important to point out that fuzzy logic as a part of a process control structure does not necessarily only mean FLC but also that utilizing fuzzy logic tools in decision-making logic and expert systems provides many new possibilities. This is discussed in more detail in later sections in this thesis.

4. Control of CFBC

It is difficult to find discussions concerning the control of a CFB boiler. Authors such as Dukelow (1991) and Huhtinen *et al.* (1994) do not find any dramatic differences between CFB and other types of boilers. The controls for the circulating fluidized bed type of boiler are introduced as similar to the bubbling bed type. This might be true if the discussion relates to the basic process control, but many differences exist between the two main types of the fluidized bed boilers. Below are presented the basic level control solutions for a typical CFB boiler and suggested improvements to the control performance.

4.1. CFB control concept

Main control loops in a CFB boiler can be listed as follows:

- Steam pressure (boiler load) control,
- Flue gas O_2 content control,
- Combustion air distribution control,
- Drum level control,
- Superheated steam temperature control,
- Combustion chamber pressure control,
- Bed pressure control,
- SO_2 control (depending on the used fuels).

These control loops, in conjunction with boiler safety interlocks, constitute the basic automation level. In Figure 20, three main cascade control structures in a typical CFB boiler are shown.

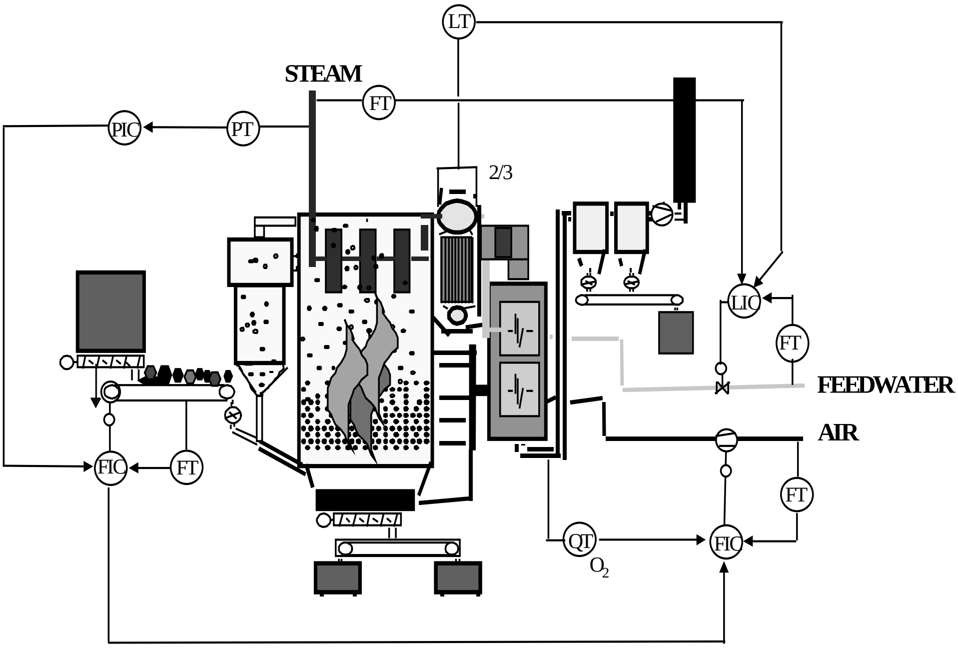


Fig. 20. A schematic layout of the main cascade loops in a typical CFB boiler.

Steam pressure (boiler load) deviation, which in practice means changing load demands coming from either steam turbine (electricity) or process plant (steam), are handled by boiler fuel input.

In general, the two main types of steam pressure control arrangements are the boiler-following and turbine-following modes. In boiler-following control, the control systems for the boiler and turbine are separate and uncoupled. Starting with steady-state loading, any control system demand for more electric power is applied only to the turbine. In the turbine-following mode, the demand for increased MW rate is used to increase the firing rate. As additional steam energy is obtained from the increasing firing rate, the steam pressure tends to rise. This causes the turbine throttle-back pressure control to open the turbine valves. (Dukelow 1991.)

Simultaneous use of several fuels is common in CFB boilers. Usually, one fuel is selected to take care of load changes and the others provide base load.

In Figure 21, a PID-type control solution in which the steam pressure controller gets a correction term from the steam flow is shown. The ratios between separate fuels are adjustable. Each of the separate fuel flow controllers get the set-point from the steam pressure controller based on the fuel ratio settings and existing constraints.

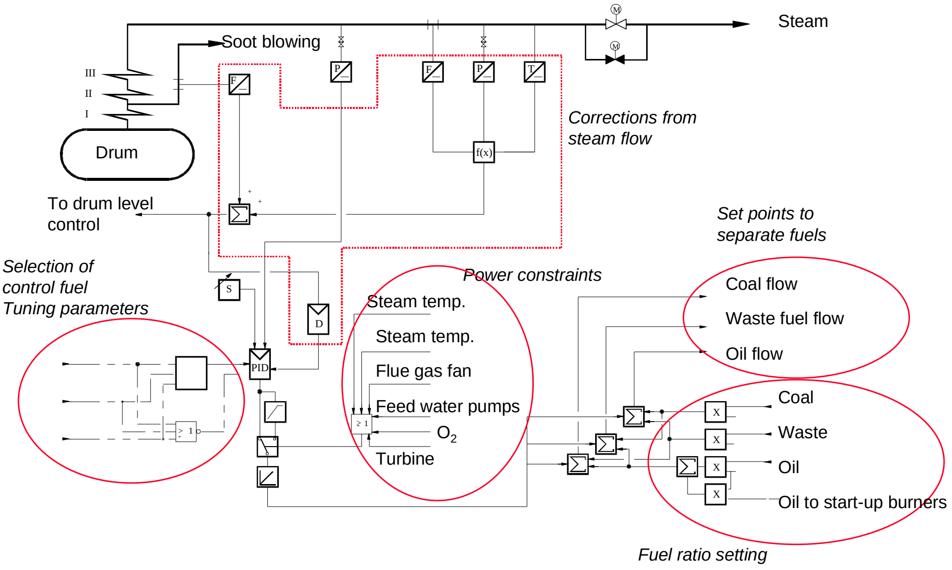


Fig. 21. A control diagram example of steam pressure control (Adapted from Honeywell 1994).

When boiler fuel input is changed, corresponding changes are made to the air controls. During all load changes, the combustion conditions and flue gas emissions must be continuously monitored, and if any disturbances are noticed, then corrective control actions must be taken.

Combustion air controls are very important for burning conditions. More stable burning conditions allow a decrease in the excess air ratio, thus reducing nitrogen emissions and increasing thermal efficiency of the boiler. However, the air controls must also take into account the potential risk for the CO and hydrocarbon emissions if excess air is reduced to too low a level.

Combustion control tasks cover air vs. fuel flow calculations for each load level (Fig. 22) including total air and primary (Fig. 23), secondary and tertiary (possible) air ratio calculations and control as well as the O_2 trim (Fig. 24).

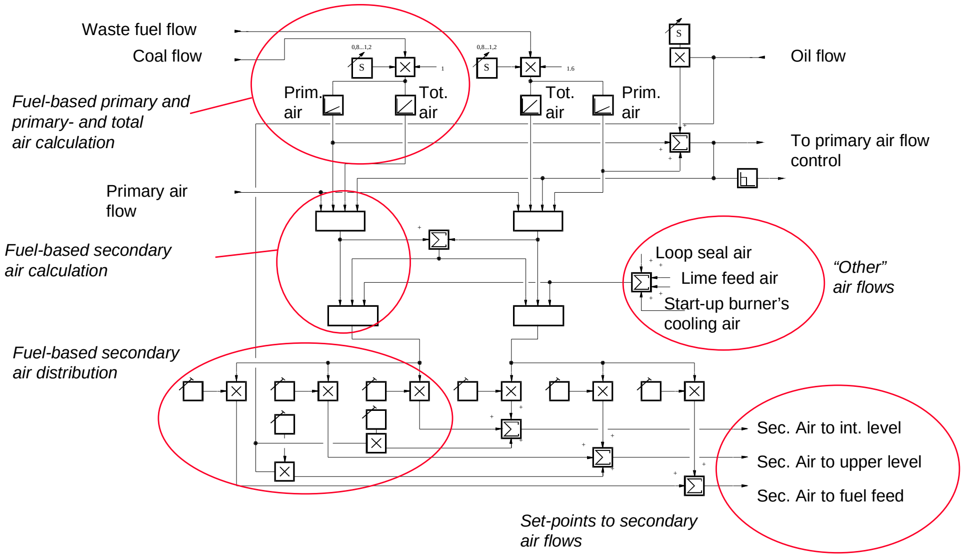


Fig. 22. A control diagram example of combustion air distribution calculation (Adapted from Honeywell 1994).

The total combustion air requirements are calculated based on separate fuel, like coal and waste flow into the combustion chamber. The elementary analysis of the fuel can also, sometimes, when possible, be used and the combustion air requirement control becomes more precise.

The total air requirement is divided between primary, secondary and tertiary (possible) air, taking into account their independent air distribution curves for different boiler loads. Secondary air, just as with primary and tertiary, has its own independent air distribution calculation for all boiler loads. The air distribution curves are calculated throughout the boiler load range. Typical constraint is minimum air at low boiler load.

In Figure 23, a typical example of primary air control structure is shown. The secondary air normally has a similar type of structure.

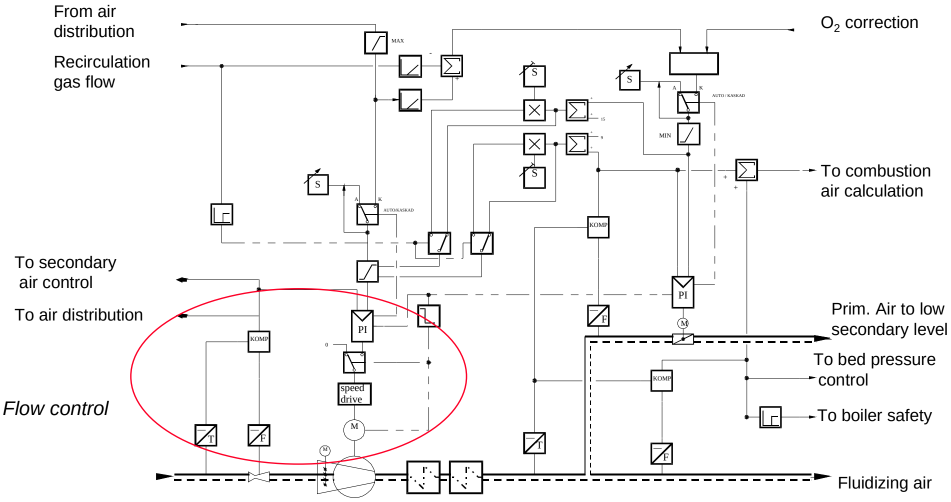


Fig. 23. A control diagram example of primary air flow control (Adapted from Honeywell 1994).

The calculated secondary and tertiary (possible) air flows are corrected based on the O_2 and sometimes CO measurements of the flue gas. So-called O_2 trim is normally tuned to be rather slow and it makes only O_2 level corrections if the O_2 measurement is moving too far from the set-point. If the steam flow is too small, the influence of the O_2 trim correction is ignored.

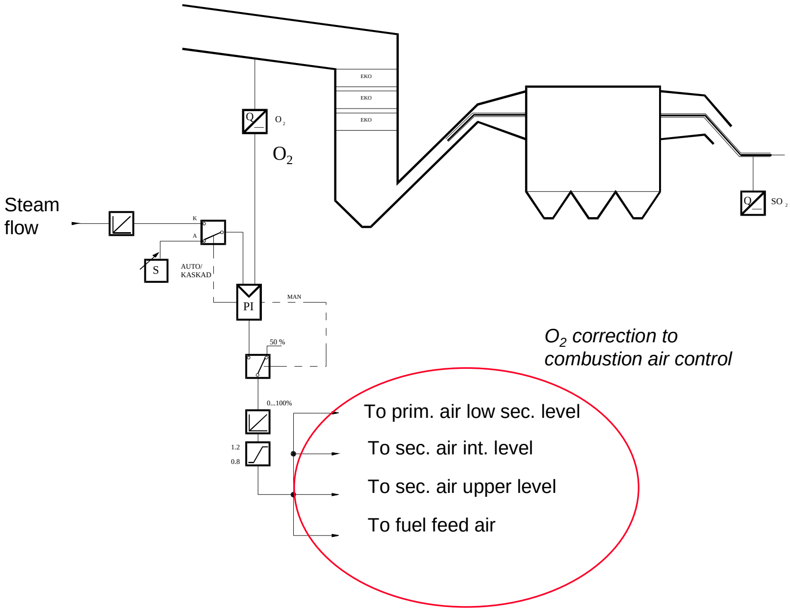


Fig. 24. Typical solution of O_2 correction (O_2 trim) to combustion air control (Adapted from Honeywell 1994).

Drum level is typically controlled by a three-element control in which the measurements of drum level, steam flow and feed water flow are used (see Fig. 25). The drum level measurement is made by three separate sensors and compensated by pressure measurement. Usually, the level signals are compared and an alarm is given if the deviation is too great.

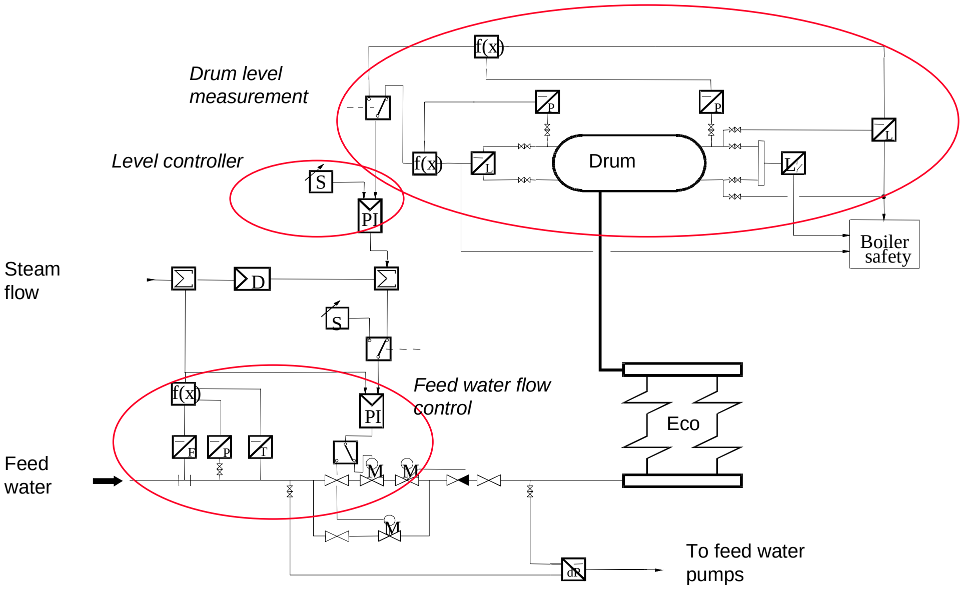


Fig. 25. A control diagram example of drum level control (Adapted from Honeywell 1994).

Steam temperature, being one of the most important parameters in boiler control, is controlled by spray water. The control structure depends on the amount of superheaters, but typically, steam temperature is the controller in stages over each superheater.

Steam flow and fuel-feed flow can be used as feed-forward correction terms in order to compensate disturbances coming from load changes. Figure 26 depicts one typical solution for final stage of steam temperature control.

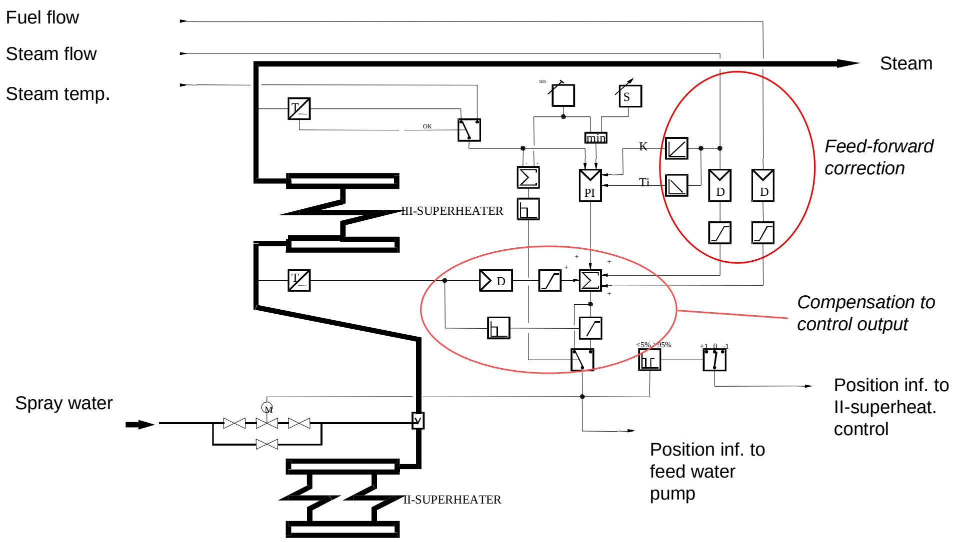


Fig. 26. A control diagram example of final stage of steam temperature control (Adapted from Honeywell 1994).

In CFB boilers, the combustion takes place in the circulating bed. Combustion efficiency is dependent on bed temperature, air distribution and bed quality. Bed temperature must be maintained within certain limits, high enough to ensure safe combustion of solid fuels and low enough to avoid bed melting or sintering. The applied bed temperature depends on fuel.

Bed temperature is controlled by auxiliary fuel flow (oil/gas/coal) if very wet or low-quality fuel is inserted into the bed, otherwise with primary/secondary air ratio, primary air flow and flue gas re-circulation.

Combustion chamber pressure in atmospheric CFB boilers is controlled by flue gas fan speed. If necessary, the flue gas pressure can be used as a feed-forward signal.

Bed quality is a function of bed particle size distribution. Particle size distribution affects bed pressure, bed fluidization and bed temperature control. If bed material gets too coarse, bed pressure goes lower and bed temperatures tend to rise.

Bed pressure is controlled (see Fig. 27) by bed material removal. In case the fuel does not bring enough suitable bed material to the furnace, new make-up sand is inserted to the bed.

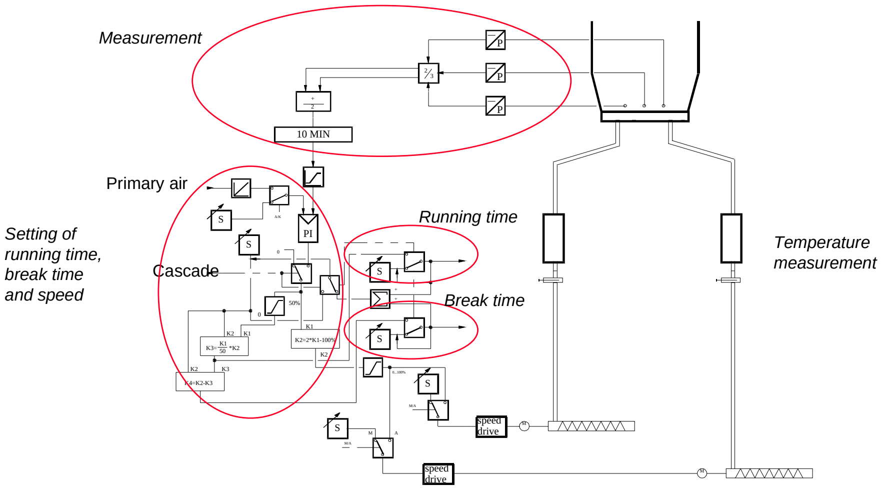


Fig. 27. A control diagram example of bed pressure control (Adapted from Honeywell 1994).

The process variables in a CFB boiler have a lot of interactions with each other. Table 5 introduces the most important interactions (see also Fig. 20), which should be accounted for when the boiler control system is designed.

Table 5. The interaction influence between the main control loops in a CFB boiler. The notation C means control action, notation X interaction and (X) marginal interaction respectively.

Control Quantity	Process quantity						
	O_2	Bed Pressure	Combustion Chamber Pressure	SO_2	Steam Pressure	Drum Level	Steam Temp.
Fuel-feed flow	X	(X)	X	X	C	X	X
Primary air flow	X		X		C	(X)	X
Secondary air flow	C		X		X	(X)	X
Bottom ash screw speed		C					
Flue gas fan speed			C				
Lime feed flow		(X)		C			
Feed water flow					(X)	C	
Water spray flow					(X)		C

The control strategies vary significantly from boiler to boiler depending on factors such as fuel type or boiler structure. The boiler's role in the power block can also require different control strategies.

4.2. Suggested control enhancements

Although the basic control structure for the CFB boiler does not appear often in boiler control literature, many researchers have done studies and experiments to improve the control. Speaking about the Fluidized Bed Combustor (FBC) in general, the discussion often concerns fluidized bubbling bed-types of boilers, which have many similarities but also some differences with the CFB boiler. Because the similarities do exist, the discussion is extended to the control of the fluidized bubbling bed boiler.

Kurjatko and Placer have introduced in their paper (Kurjatko & Placer 1991) an Inferential Smith Predictor Controller (ISC) to control NO_x emission and bed temperature in a 20 MW petroleum coke-fired circulating fluidized bed boiler developed by the Combustion Power Company.

A Smith Predictor is a first-order dynamic model with dead-time to predict the current value of the process variable based on past values of the control output. Any difference between the predicted and actual process variable is an indication of a process disturbance and a change in the control output is required. As a result, the combination of a filter equation and the ideal feed-forward controller resulted in Fig. 28, which shows the schematic picture of the feed-forward controller. Within the dotted line is the configuration of the basic Smith Predictor controller, where τ_F is controller time constant, τ_M process model time constant and K_M process model steady-state gain. τ_F is the only tuning parameter of the Smith Predictor controller they used. It establishes the desired controller response to process disturbances and set-point changes. Dead-time, process gain and time constant were established after several trials. Concerning dead-time, they rather overestimated than underestimated it.

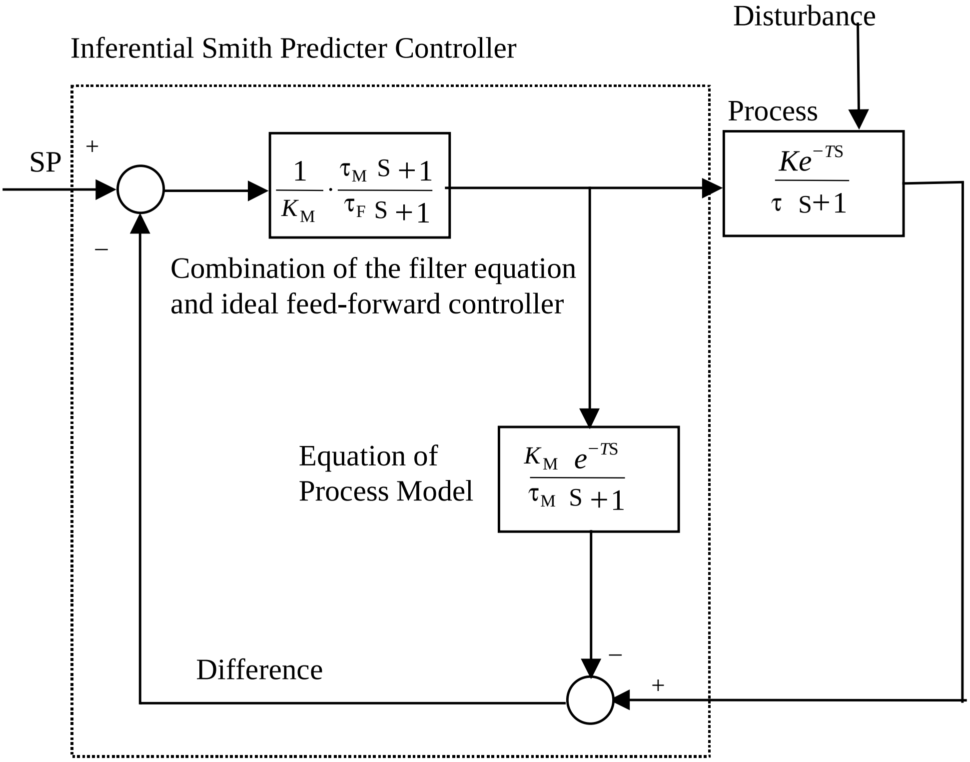


Fig. 28. Inferential Smith predictor for fluidized bed boiler control (Redrawn from Kurjatko & Placer 1991).

In the application of NO_x control the NO_x emissions were reduced by ammonium (NH_3) injection. The ISC was chosen as a slower master loop in a cascade structure acting as set-point to the slave loop, which is PI-type ammonium flow control. In the case of bed temperature control, the master ISC loop is the bed temperature controller giving set-point to the fuel-feed flow to the combustor. In the NO_x, control the process dead-time was 90s and for bed temperature control 900s. Their conclusion was that the fixed model ISC provides an algorithm that was better than the standard PID for processes with significant dead-time.

A few other model-based control examples for the CFB boiler have also been discussed in the literature and research papers. A German research group (Petersen *et al.* 1989) suggested model-based load control for the CFB boiler by utilizing a combustion chamber model. They developed a mathematical model of a linear steam generator for fluidized bed firing system.

The two most important results of their examination/experimentation are the improved control behavior of the controller compared with the PID controller at quick load changes and the improved disturbance behavior due to pulsating bed material in the fluidized bed.

The control structure depicted in Fig. 29 (Ikonen 1994, Åström *et al.* 1993) has been proposed to optimize long-time behavior of the combustor. In the upper stage, the long-term operation of the process is optimized while the lower stage takes care of the process disturbances. For long-term optimization (Henttonen *et al.* 1992), the emissions have to be taken into account. The purpose of the emission models block is to calculate optimal set-point values for the actual process controllers by minimizing a given cost function.

In the control structure, the most interesting part is the influence of the bed inventory to the boiler control. It formed a dynamic process model describing the dynamic behavior of fluidized bed combustor from primary air and coal feed to oxygen combustion. Using the parameters of the models identified in different steady states, it was possible to classify model parameters according to bed fuel inventory. The parameters of same model structure were also successfully estimated by recursive algorithms. The same kind of correlation was found with the parameters of the recursively identified linear model. The main problem when using these algorithms was to achieve simultaneously both robust and parameter-sensitive behavior. (Åström *et al.* 1993, Ikonen & Kortela 1994.)

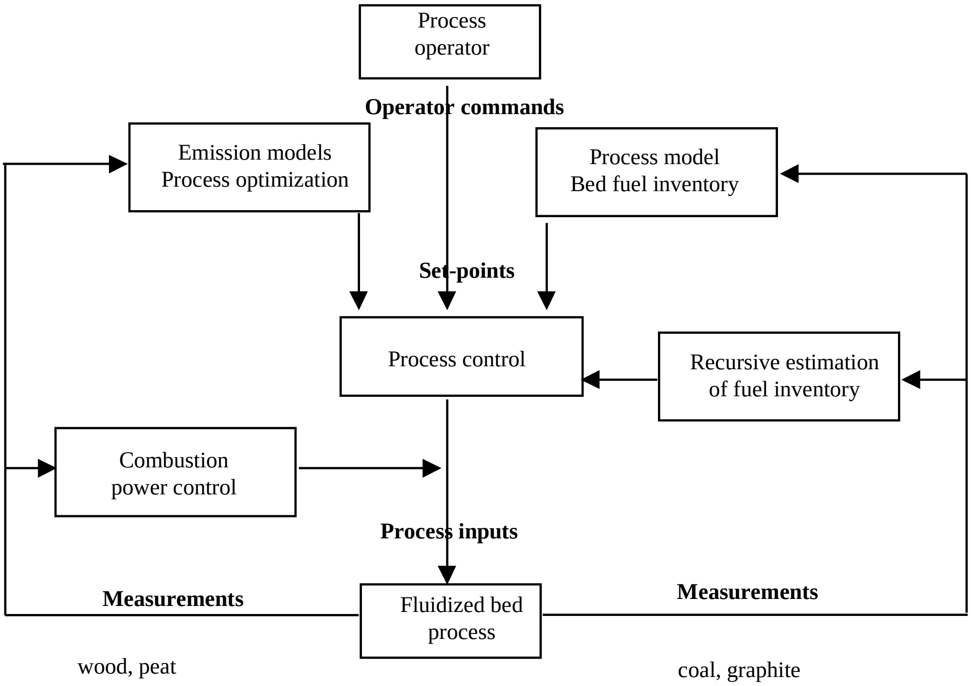


Fig. 29. A control structure for a multi-fuel fluidized bed combustor. Lower level controller parameters adapt to bed carbon content when burning fuels that form fuel inventory. Combustion power control is an important stabilizing control with bio-fuels. Higher level includes process set value optimization with respect to emissions and thermal efficiency. (Ikonen 1994, Åström *et al.* 1993.)

According to researchers (Kortela *et al.* 1991, Trast 1994), the fuel inventory in the bed is one of the key variables in the combustion process; combustion rate, and formation of nitrogen and sulfur oxides. They have proposed a multi-variable control strategy for the fluidized bed boiler depicted in Figure 30.

The control structure accomplishes combined O_2 content in the flue gas and bed temperature control. If there is enough fuel in the bed, the bed temperature changes can be made faster by burning the excess fuel inventory with primary air. The conventionally-used control loops (oxygen content in the flue gas–primary air flow and temperature–fuel-feed) will start with fuel-feed and when the oxygen content in the flue gases decreases the primary air feed will grow. This will cause very strong oscillations. (Kortela *et al.* 1991.)

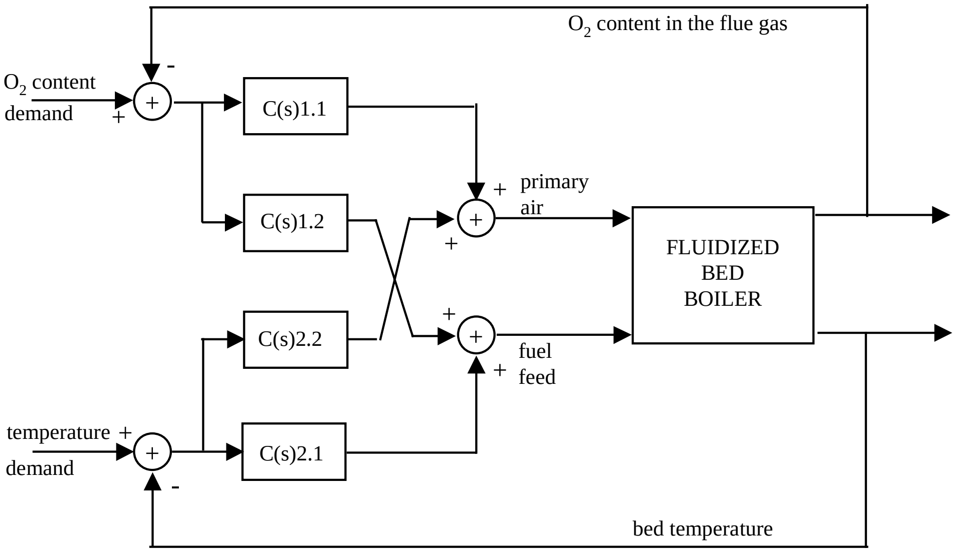


Fig. 30. Multi-variable control strategy for the fluidized bed boiler. The flue gas O_2 content can be controlled by primary air feed or fuel-feed. Similarly the bed temperature can be controlled by the same variables. Combining these controllers is possible to propose parallel multi-variable control structure for flue gas O_2 and bed temperature control. The control blocks (C(s)1.1) etc. are normal P- or PI-type controllers. (Kortela *et al.* 1991, Trast 1994.)

This kind of system works very well at one operating point, but in the case of non-linear processes the tuning is difficult. The fuel must contain low amounts of volatile compounds in order to keep high fuel content in the bed (Trast 1994). It is also important to keep the bed inventory well controlled so that it can not become too high, causing the danger of high bed temperatures and sintering threat.

For the CFB boiler, the increased bed char inventory potentially exists when the fuel contains a lot of non-milled coal particles. In multi-fuel use, as is often found in the pulp and paper industry, the amount of coal is normally minimized and the bed inventory exists only in very special circumstances, such as during bio-fuel-feeding disturbances when the steam must be generated by using some support fuel like coal. The continuous load changes and fuel grade fluctuation also generate so many disturbances that the above-proposed multi-variable control strategy can meet very big challenges. In the case of a utility CFB boiler, it might be worth testing.

The basic idea for the combustion power control for the peat-fired boiler was suggested in the early 1980's (Wahlström 1982, Lehtomäki *et al.* 1983). The main idea in the Combustion Power Control (CPC) (see Fig. 31) is to stabilize the burning conditions in the combustion chamber when burning non-homogeneous fuels. More stable burning conditions provide the possibility to decrease the excess air ratio reducing nitrogen emissions and increasing the thermal efficiency of the boiler.

The disturbances in fuel-feed rate and fuel quality are detected by calculating the oxygen consumption and estimating the combustion power by means of total air flow and oxygen concentration measurements. The measurement of the fuel-feed rate may also be used to improve the estimate of the flue gas flow and thereby to correct the oxygen consumption calculation. The amount of fuel actually burned in the combustion chamber (the combustion power) can be calculated from the oxygen combustion estimate. A compensation of the fuel-feed rate is then made to stabilize the combustion power and thereby to stabilize the furnace conditions and the oxygen content in flue gases. In this way the disturbances in fuel power can be detected and compensated for before they affect the steam pressure This control procedure was tested at Chalmers University Power Station (Sweden) in a 8 MW(th) CFB boiler. (Åström *et al.* 1993, Ryd 1994.)

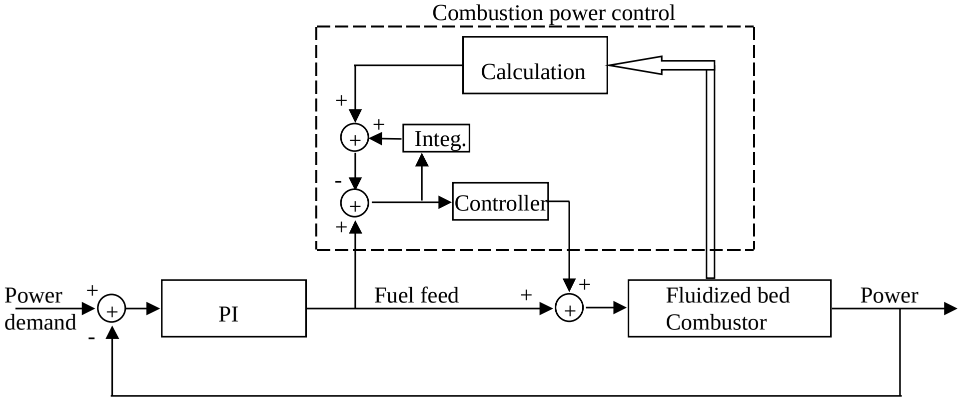
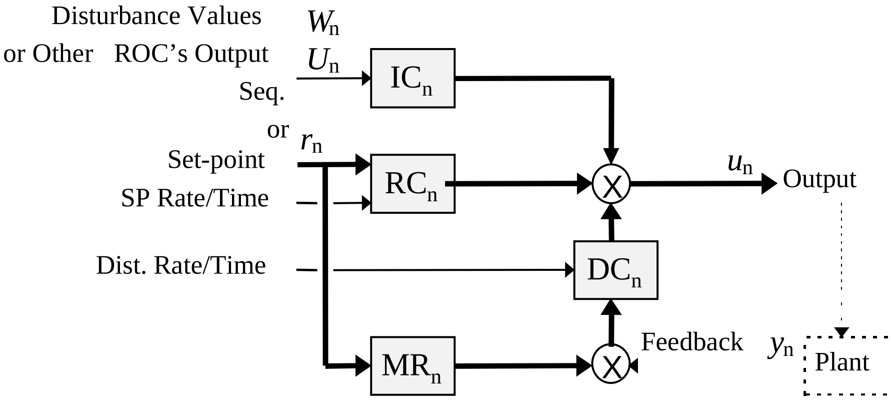


Fig. 31. Simplified control structure of CPC for fluidized bed combustion. The fuel-feed rate and fuel quality are compensated with the fuel-feed rate itself. The disturbances are detected by calculating the oxygen consumption and estimating the combustion power using total air flow and oxygen concentration measurements from the combustor. (Ryd 1994, Åström *et al.* 1993, Kortela *et al.* 1991.)

Multi-variable control (Jonas 1997) has been tested in a 75 megawatt fluidized bubbling bed unit. The type of controller is Multi-input Multi-output (MIMO) model-based controller termed Rate Optimal Control (ROC).

ROC is a multi-variable model-based finite horizon controller with a two-port design and constrained trajectory control objective. It is this two port design of ROC that provides separation of reference (set-point) control and disturbance (feedback) controls. The basic structure of the ROC is depicted in Fig. 32 (Jonas 1997).



RC - Response Controller (Set-point)

IC - Interference Controller (Known Disturbances)

MR - Model Reference

DC - Disturbance Controller (Unknown Disturbances)

Fig. 32. Rate Optimal Controller (ROC). The base line control signal is generated by the Model Reference processor (MR_n), which moves the plant into the desired state (y_n) by way of the user-specified straight line trajectory. The Disturbance Controller (DC_n) responds to the discrepancy from the planned trajectory and produces a disturbance control signal to bring the controller back to the planned trajectory by way of a user-defined disturbance trajectory. The reference processor and disturbance processors can be independently set for either rate response (e.g., MW/min) or time response (e.g., 1.2 minutes). This rate feature of ROC provides simple "tuning" that requires only to specify the reference rate (or time) and disturbance time (or rate). (Jonas 1997.)

The architecture of the ROC for fluidized bed application is shown in Fig. 33. Five ROCs were designated for bubbling fluidized bed control. The selection of the dominant pairing, load measurement to fuel control and throttle pressure to governor valve, was an important consideration. While the ROC system can fully coordinate these control movements, the dominant pairing determines how the boiler-stored energy is to be utilized.

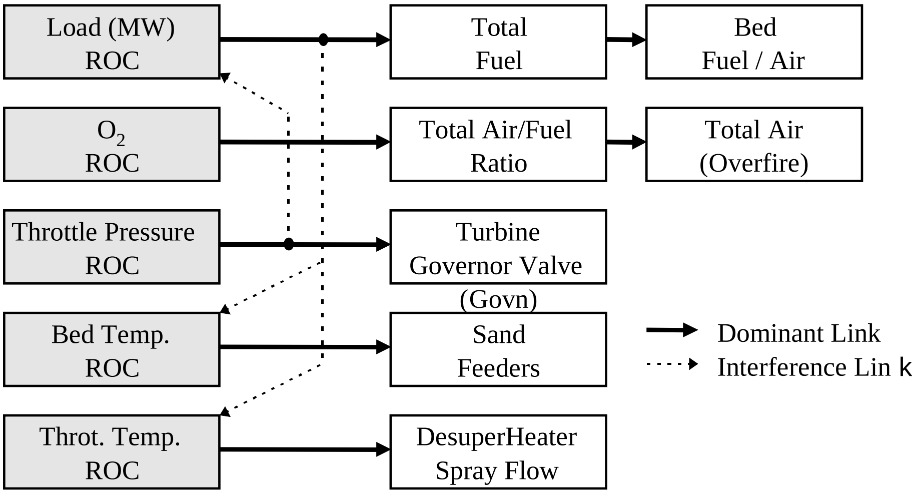


Fig. 33. Bubbling fluidized bed ROC architecture (Jonas 1997).

The above introduced control ideas for fluidized bed boilers are examples found from the literature. Surely several more applications and control experiments are made in control development projects, but many of these are not publicly reported in the literature.

The applications discussed later on this thesis are partly following the ideas introduced above such as combustion power control and bed fuel inventory estimation. Because the basic principle of the research project for this thesis was to test the suitability of fuzzy logic control in industrial multi-fuel CFB boiler control challenges, the capability of the applications discussed above do not make it possible to accurately evaluate these enough. Many of these could also be very interesting to test in a multi-fuel CFB boiler environment.

4.3. Fuzzy logic control solutions for fluidized bed boilers

In the research literature, only a few of examples of fuzzy logic applications on CFB boilers were found. To achieve a better understanding of the fuzzy solutions for Fluidized Bed Combustion (FBC) control that have been developed, the fuzzy solutions implemented on Bubbling Fluidized Bed (BFB) boilers are discussed as well. In the last part of the chapter, fuzzy solutions implemented on other boiler types are listed. The controls implemented on these boilers are general and can be modified to CFB boiler control.

4.3.1. Fuzzy solutions to CFB boilers

Pyykkö and Uddfolk (Pyykkö & Uddfolk 1997) introduced a fuzzy approach to CFB combustion air feed distribution control. Their study was completed in a utility CFB boiler in Rovaniemi, Finland. The boiler's main fuel is milled peat. In the fuzzy logic-based control strategy, depicted in Fig. 34, they introduce a scheme which controls and corrects combustion air feed distribution automatically and additionally calculates the set-point for O_2 controller. The system replaces previous manual control. The main criterion in the fuzzy decision-making are temperatures measured from different parts of the combustion chamber, combustion air flows, fuel power and flue gas analysis. They calculate the fuel heat value and utilize the calculated heat value in the combustion air control.

As a result of the fuzzy logic air distribution control, Pyykkö and Uddfolk report improved combustion air control and decreased bed temperature deviation. Although the test environment in this case does not appear to be very challenging –utility boiler with one main fuel– the result can be accepted since, normally, the combustion air control with existing excess air is a weakness in the CFB control structure. It would be interesting to see the benefits of this kind of combustion air distribution control in an industrial multi-fuel boiler with continuous fuel heat value fluctuation.

The main reasons why the fuzzy approach was preferred were good performance in changing operation environment with varying fuel quality and possibility to replace previous manual control by automatic control actions.

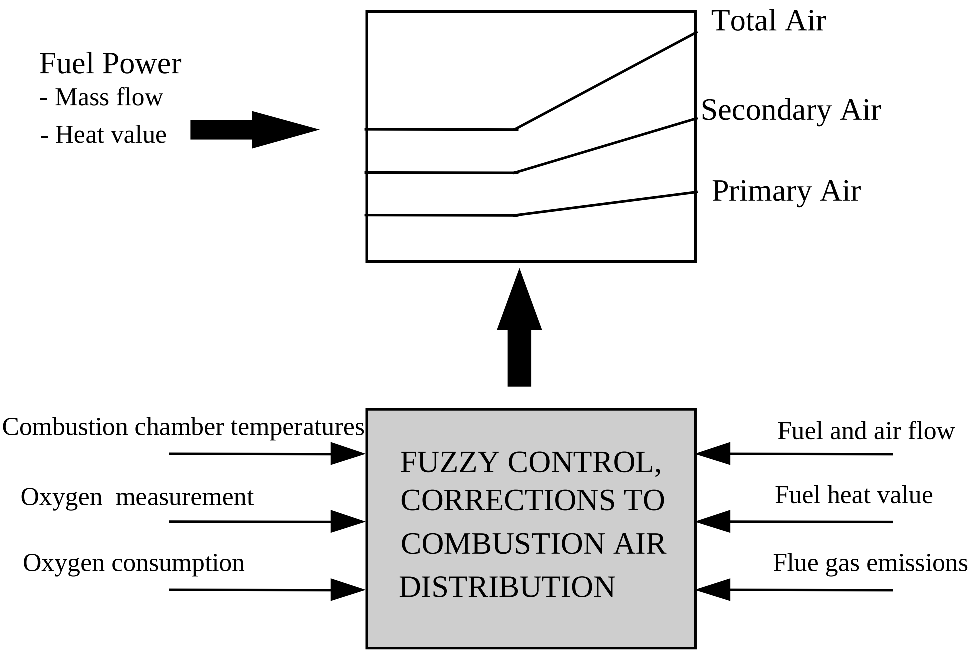


Fig. 34. Combustion air distribution controlled by fuzzy logic (Redrawn from Pyykkö & Uddfolk 1997).

Stone-Consolidated's West Tacoma mill has applied a fuzzy logic approach to control its multi-fuel boiler. In a survey paper, the authors (Bhatia *et al.* 1996) describe a fuzzy air/fuel-coordination optimizer depicted in Figure 35.

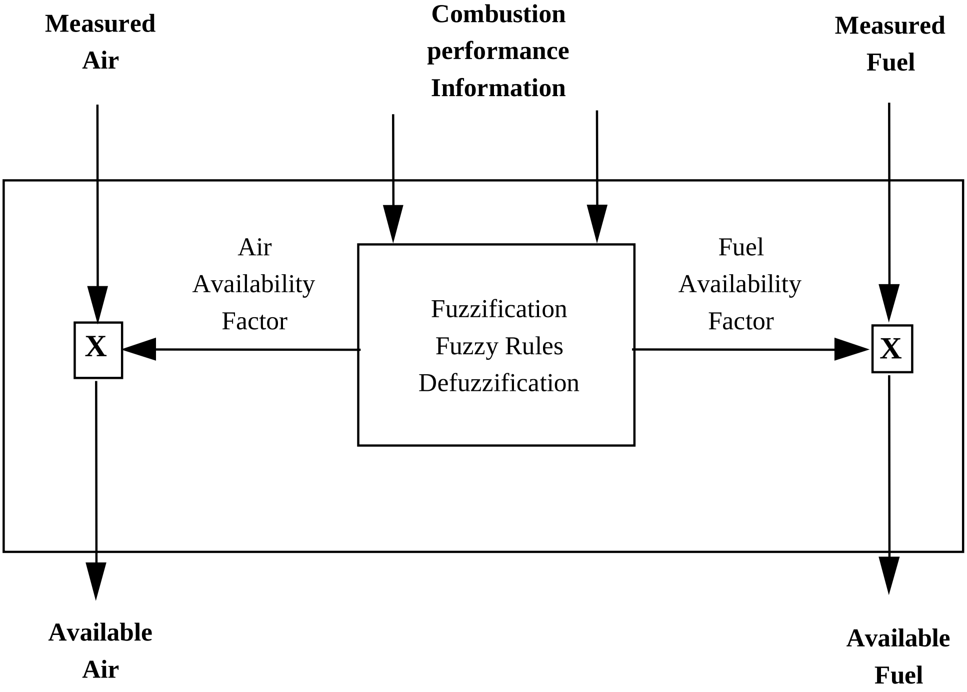


Fig. 35. Fuzzy air/fuel-coordination optimizer (Redrawn from Bhatia *et al.* 1996).

The fuzzy air/fuel-coordination optimizer takes combustion performance information and calculates an “availability factor” for air and fuel. The factors are multiplied by measured flows to produce “available air” and “available fuel” values. “Available” values are used as control variables for conventional feedback control strategies. The input variables used in the fuzzy system are percent O_2 error from a normal set-point value and percent heating value from a normal set-point value.

According to the authors (Bhatia *et al.* 1996), the fuzzy logic approach simplifies conventional optimization techniques by introducing easily understandable control variables called “available” and “measured” values. An optimizer based on fuzzy logic generates available factors for air and fuel based on applicable performance information, specific to the combustion process. The measured air and fuel are redefined through the availability factors into conventional air/fuel-coordination strategies. This methodology addresses overall control performance and combustion process operation. The fuzzy approach was used for air/fuel-coordination optimization because relationships between variables are not easy to define through mathematical models. (Bhatia *et al.* 1996.)

Models for the emission of the sulfur dioxide to create a proper SO_2 emission controller have been developed (Domanski *et al.* 1998). Their modeling process started with different types of structures: a classical linear model, a neural network model, a fuzzy Takagi-Sugeno model and a standard Mamdani-type fuzzy model. The identification and modeling were performed for the circulating fluidized bed boiler with 450 tons per hour steam production. The boiler is located at Warsaw power plant EC Zeran.

Inputs for the fuzzy non-linear model they developed are:

- Steam flow,
- Primary air flow,
- Sorbent quantity (k) moment,
- Sorbent quantity (k-1) moment,
- Temperature at level 2,
- Temperature at level 4,
- Past SO_2 emission (k-1) moment,
- Past SO_2 emission (k-2) moment.

As a result, it was discovered that the multi-regional Takagi-Sugeno model implemented as a Fuzzy Neural Network (FNN) was the best fit because being a combination of fuzzy logic and neural network system, the models were less complex and so easier to accept by the technology staff in the power plant. It was selected as a non-linear process model for the control system design in future. (Domanski *et al.* 1998.)

Examples of using fuzzy neural networks to model semi-circulated fluidized bed boiler's flue gas emissions are also described in the research literature (Ikonen & Najim 1996 and Ikonen 1996). In these parameterized experimental models, the ability to obtain non-linearity from fuzzy neural networks have been continuously utilized.

4.3.2. Fuzzy solutions to bubbling fluidized bed boilers

Fuzzy logic has been used as an alternative approach for start-up control and normal regulation of a coal-fired bubbling fluidized bed boiler (Koffman *et al.* 1996). Control inputs for this system were fuel-feed rate, primary air flow rate, and secondary air flow rate. System outputs were combustion bed temperature and oxygen percentage in flue gas indicating boiler's efficiency.

The form of each rule set (see Chapter 3) used was as follows:

- If temperature is LOW / OK / HIGH and temperature change is POSITIVE LARGE / NEAR ZERO / NEGATIVE LARGE, then secondary air flow rate adjustment is LESS / NONE / MORE,

- If oxygen is LOW / OK / HIGH and oxygen change is POSITIVE LARGE / NEAR ZERO / NEGATIVE LARGE then primary air flow rate adjustment is LESS / NONE / MORE,

- If oxygen is LOW / OK / HIGH and coal feed rate error is POSITIVE LARGE / NEAR ZERO / NEGATIVE LARGE then coal feed rate adjustment is LESS / NONE / MORE.

Koffman *et al.* (1996) compared the fuzzy logic control to conventional PI control. The result indicated that the fuzzy logic control is better in boiler start-up because of its much lower primary air flow requirement for good oxygen control, but PI was better in normal operation due to its quicker rejection of disturbances. The fuzzy logic controller's sampling time took up to 20 seconds and was chosen based on the human operator's capability to perceive sufficient system response to previous actions; "wait and see" while the PI controller's sampling time was only 0.6 of a second. Although, as a result, it was stated that a faster fuzzy logic controller may perform better than PI controller, in which case fuzzy control could be used exclusively. (Koffman *et al.* 1996.)

4.3.3. Fuzzy logic solutions to other types of boilers

A fuzzy logic-based steam temperature control in a fossil power plant simulator has been tested by Sanchez (Sanchez *et al.* 1995). They reported that fuzzy logic was a suitable control method for steam temperature when there is no simple mathematical model of the process available or when the mathematical model is too complex to be evaluated fast enough for operation in real time, or needs too much memory in the designed architecture.

In the fuzzy logic controller approach, they used seven fuzzy sets to describe both steam temperature error and those derivatives of errors and seven fuzzy sets were chosen to describe manipulation actions: attemperation flow and slope of burners.

When compared with PID control, fuzzy logic control was found to give better results since it reduces overshoot and undershoot when the process is subject to significant load changes.

Regarding the use of fuzzy control in practical situations, Sanchez (Sanchez *et al.* 1995) found it likely that a combination of the operator's experience in control actions and a fuzzy model of a process would be necessary to construct an effective method for the derivation of fuzzy control rules.

Ghaffari and Asl (Ghaffari & Asl 1994) have compared the response of conventional feedback control system (PID) and the response of fuzzy logic control for the de-superheater section of a drum-type steam generation plant. They implemented an FLC with nine membership functions for steam temperature error and change in error. The steam temperature was controlled by the spray water control valve and the output was also defuzzified to nine phases (membership functions). According to their response (steam temperature) tests, the application of FLC improves the behavior of the system by resulting in smaller overshoot and shorter settling time than PID control. They have also tested two types of inference mechanisms. In their studies, the algebraic product was shown to give a slightly smaller overshoot and shorter settling time than the MIN function.

A self-tuning (gain-scheduling) PID controller using a fuzzy logic approach has been proposed by Lee (Lee 1995). The controller was applied to the control the drum water level process of a boiler in an electric power generating plant. In such a power plant the "swell and shrink" phenomenon is due to rapid changes in pressures and temperatures in the drum. Due to large physical dimensions of the drum, the "swell and shrink" effect in the drum water level process is significant and the water level measurements are often inaccurate and noisy. Consequently, it is a daunting task to derive a parametric mathematical model which is valid over a wide range of operating conditions.

One major downfall of a conventional self-tuning controller has been the requirements of an accurate or a good model of the process and the inability to set meaningful goals for the adaptive mechanism. The fuzzy logic-based gain-scheduling controller gave good performance because it managed to deploy a set of heuristic rules and procedures derived from the profound process knowledge obtained from experienced skillful control engineer’s and plant operator’s knowledge of the plant operations and plant behavior and other plant operational records. (Lee 1995.)

The difficult process of a municipal waste incinerator boiler was studied by Lausterer (Lausterer 1995). The basic problems associated with municipal waste incineration are varying non-homogeneous fuel resulting in a strongly fluctuating heat release with high thermal stressing of boiler and turbine; furthermore, the danger of increased CO emissions with poor combustion. Typically, many manual interactions are necessary to stabilize plant operation. The fuzzy logic controller Lausterer implemented on a waste incinerator in Oberhausen, Germany, uses as inputs steam flow, O_2 in flue gas and extinguishing criterion. The extinguishing criterion means poor combustion due to poor inflammability of the waste and due to poor air access to high a waste build-up. The criterion is derived from a simple dynamic network using measurements of the steam flow and the feeder speed and an identified mathematical model of the process. The outputs are primary and secondary air flow, waste feeder speed, and speed of rollers.

Lausterer reports a long list of benefits from the use of a fuzzy logic controller in a waste incinerator process where fuzzy logic offers a simple and easily comprehensible method to tackle even very complex control problems, if only enough knowledge is available on the correct control actions. The benefits were achieved mainly because the previous manual control actions were possible to automate by fuzzy logic.

The suitability of the FLC control for a waste fuel incinerator plant has also been studied by Gierend (Gierend 1996). He implemented a FLC control system on a waste incinerating plant in Mannheim (Germany). In that fuzzy logic controller, the inputs were flue gas O_2 content, primary air flow (zones 1&2), furnace temperature and change of steam production. The outputs were set-points to primary air flow (zones 1&2) and fuel-feeder speed. The knowledge base for the controller was done by utilizing operators’ and process engineers’ expertise.

The above-introduced fuzzy control ideas for fluidized bed boilers are examples found from the literature. Many of the proposed fuzzy systems are reported to improve the boilers’ control performance significantly, but deeper analysis of the fuzzy controllers’ structure and reasons why the fuzzy approach did help to obtain good results is not available.

The applications discussed later on this thesis are not based on the ideas introduced above because the basic principle of the research project for this thesis was to test the suitability of fuzzy logic control in industrial multi-fuel CFB boiler control challenges, and a similar approach was not successfully found in the literature.

4.4. Unsolved CFB combustion control problems

Even if boilers are well designed and conventional control systems are modified to control all types of combustion methods, real life experience has demonstrated that there are still many unsolved problems causing unstable control situations as well as losses of efficiency and higher emissions (Karppanen 1997).

4.4.1. Control of fuel-feed

In bio-fuel combustion, and especially in the case of multi-fuel-feed, one of the greatest difficulties is the fuel heat value fluctuation in the feed flow caused by the non-homogeneity of the fuel to be burned in the boiler. The energy content of the fuel mix is difficult to measure continuously online in industrial boilers (Järvinen 1998a). Even the measuring of the moisture from the varying fuel mix has proven to be very difficult and hardly used in the case of multi-fuel boilers.

The heat value can vary much within a short time period depending on the fuels used and the quality of the mixing process of the different fuels. Additionally, due to insufficient mixing, the grading by size and weight of different fuel types takes place in silos and conveyors (see Fig. 6) and causes fluctuation in fuel quality. The main factors causing quality differences are moisture and ash content of the separate fuels. Because the insufficient pre-mixing and grading the continuous fuel-feed flow actually consists of pulses of separate fuel types with heat values greatly differing from each other.

The fuel heat value fluctuation causes many problems in the normal boiler control since its disturbing effect is fed back normally from the steam pressure. When the fuel input contains less energy per time unit, because of lower heat value, the steam pressure tends to drop and rises if the fuel contains more energy, respectively. The result is unstable boiler control and low efficiency. In the worst cases, the steam delivery capacity to the consumers, e.g. paper mills, can be at risk.

According to the data gathered from the Varenso K6 industrial boiler, the fuel heat value can vary a lot. Figure 36 shows the steam production ability of the normal waste fuel (kg steam/ kg bio-fuel) during week 43, 1997. The average steam production is 1.5 kg steam by 1 kg bio-fuel and the fuel fluctuation is about +/- 20 %. The absolute relation is not correct because of measurement errors in the mass flow of the waste fuel, but the figures can be handled as relative.

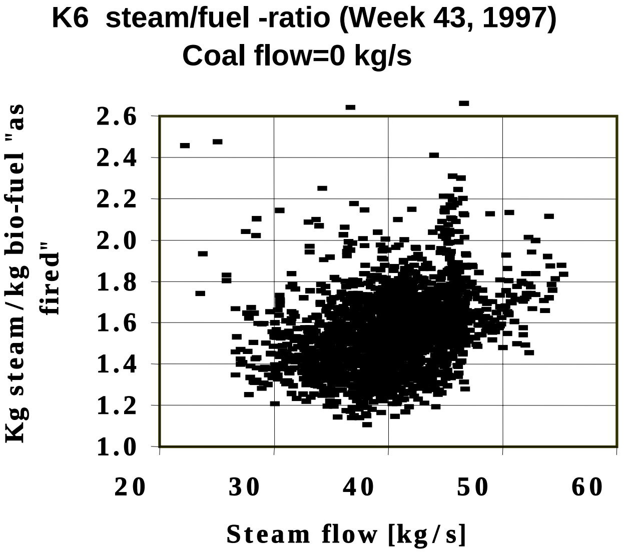


Fig. 36. The waste fuel-feed relation to the steam generation at different steam flow (load) rates during week 43, 1997 in Varenso CFB boiler K6. The unit (kg steam/ kg bio-fuel “as fired”) means the amount of steam production per amount of fed bio-fuel and its variation indicated the changes of the fuel heat value during the studied period.

The changes in waste fuel quality are quite often handled by feeding so-called support fuel like gas, oil or coal into the combustion chamber in order to obtain a big enough base load level so that the disturbances do not play a significant role in steam production. Some special combustion process’s constraints like too low bed temperature, maximum load of flue gas fan or maximum steam production also demand support fuel-feed.

The usage of support fuel is seldom very well optimized if the operator makes decisions and manually controls the fuel-feed. For example, when two types of fuels with totally different costs are available, but the cheaper fuel can cause more problems in boiler control, the operator wants to guarantee boiler operation without worrying about the energy price. So, the control problems can be masked out without any special control arrangements, but this kind of method increases the energy price.

The CFB industrial boiler is quite often used as a swing boiler in the factory steam net. This means that the boiler must continuously take care of all kinds of steam consumption changes of the processes. Normally, load changes are controlled by the steam pressure controller, which gets its feedback from the steam pressure. This kind of control solution must be tuned to be fast enough in rapid load changes. Rapid load changes are very common when the steam consumers are paper mills.

4.4.2. Bed asymmetry

A typical problem in the combustion management of the CFB boiler is the asymmetry of the bed, which means that the combustion is not homogeneously distributed across the bed. This asymmetry is caused by volatile plumes and fuel-feeding along a single wall to the combustion chamber. The volatile plumes are results of poor gas mixing because the fuel and air feeding is not in balance and is typical in bigger commercial boilers (Grace *et al.* 1997).

Figure 37 shows an O_2 profile taken at a height of 22.5 m from a commercial 22 MW(e) boiler. It is easy to see that the O_2 level varies between 4 and 7 % from wall to wall inside the combustion chamber. The oxygen content in the boiler depicted below is rather high, but it is not very exceptional, especially in the case of multi-fuel boilers.

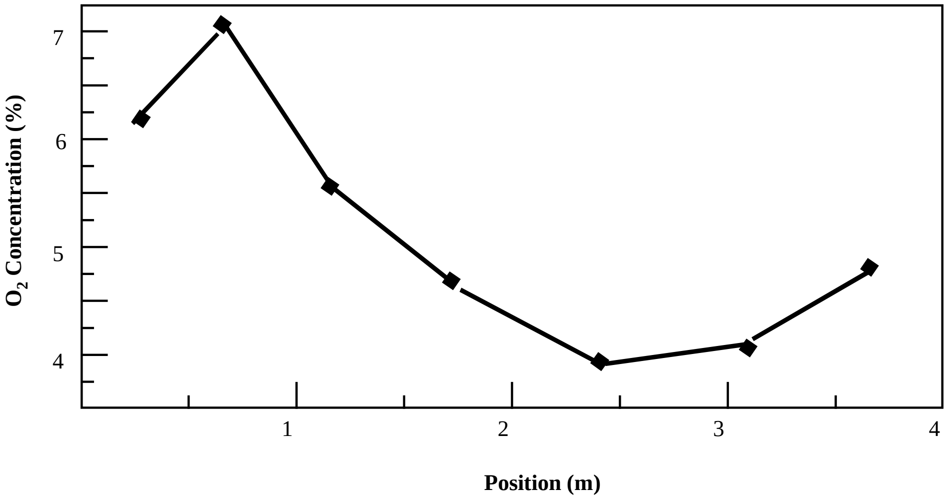


Fig. 37. Lateral gas profile in a commercial 22 MW(e) CFB boiler. The position is the distance from one wall and values are the average of three different lateral positions. Two feed chutes are positioned along the opposite wall (i.e. at 4 m). Profile shows strong radial non-uniformity. (Redrawn from Grace *et al.* 1997.)

Although the fuel-feeding into the combustion chamber is arranged properly, differences in fuel quality can cause asymmetry since the different fuel types do not flow similarly trough the conveyors (see Fig. 6, Chapter 2). As noted, in the Varenso K6 boiler, the dampers being in a certain position pass a lot more fuels like sod peat and coal than bark or cutter chips, which typically consist of longer fuel particles.

An asymmetric bed can cause many problems not only to boiler control but also to the boiler construction. If the O_2 level is asymmetric, it normally also causes a large temperature difference between cyclones and continuous thermal stress to the other cyclone (if more than one cyclone is available) and causes higher maintenance costs.

An asymmetric bed also increases excess air in many boilers since the air feed control followed for safety reasons is carried out by the minimum O_2 measurement. This naturally decreases the efficiency of the boiler and increases NO_x emissions.

Burning too high in the combustion chamber is caused by an asymmetric bed by lack of oxygen-rich sections, especially when light fuels are used. Sometimes the burning takes place not earlier in the combustion chamber than in cyclones where the burning element can be CO, volatile or light fuel particles.

4.4.3. Abnormal situations and increasing bed fuel inventory

When bio-fuel is used, all kinds of fuel-feed breaks, fuel silo bridging and freezing, or feeding system jams may occur. Most common problems in the feed systems of the multi-fuel industrial boilers are dust, complicated conveyor structures, impurities, fluidity of bark and sludge and grading of different fuels. (Järvinen 1998b.)

Feeding problems cause difficulties in keeping the boiler in control. Conventional automation systems are not able to handle control procedures, which take care of abnormal situations. Control actions during the abnormal situation have been done manually. Manual control is quite often a reasonable way to get rid of problems but typically it depends too much on operator knowledge and experience.

Other dangerous situations can be caused by the fast-increasing fuel inventory (unburned char) in the bed. In this thesis, increased bed fuel inventory means a situation when fuel-(coal) feed to the combustion chamber is much higher than the actual power need demands, and a significant amount of unburned char is gathered into the bed. The risk for this kind of situation is shown to be (Varenso K6) rather great in the case of fuel trip when a great amount of missing fuel-feed, like bark, has to be replaced by coal. In the case of manual control, the overfeed of the coal can appear because the operator notices the steam pressure drop and increases coal feed more than is needed. This is caused because the ignition time of the coal particles is rather long and the steam production decreases until the coal starts to burn properly. To solve these kind of cases, the operator must be well-trained. The amount of bed inventory in a multi-fuel boiler is rather difficult to measure and even the total sintering of the bed can take place if the bed fuel inventory is not under control.

5. Improvements to Circulating Fluidized Bed boiler control

The basic demand on the control of the multi-fuel CFB boiler is to keep the steam header pressure stable under all circumstances with the lowest possible energy cost. Fluctuations of the waste fuel mix heat value, due to fuel composition changes together with the random feed of additional fuels like coal to the bed, causes major disturbances for bed circumstances and combustion power or firing rate.

In industrial boilers, another important challenge to the control system is the rapid load changes caused by the steam users. This causes high demands on the steam pressure control, especially when the header pressure is not controlled by a turbine or steam accumulator but the boiler has responsibility for the total steam net pressure control. The steam pressure must be kept at the set-point while ensuring that the ability to prevent steam pressure drops or rises is high.

When the fuel mix consists of many different kinds of fuel like bio-fuels, fuel-feeding problems often become the biggest issue affecting boiler availability and secure steam production. The highest priority for boiler operators is not smooth steam pressure or energy price minimization, but the ability to produce enough steam without causing problems for the steam users.

Although the CFB boilers can burn wastes and other fuels in a more environmentally friendly way than some other combustion techniques, there is always a chance to obtain lower emissions. NO_x emissions can be decreased by minimizing excess air while simultaneously improving efficiency.

Normally, the multi-fuel CFB control is done using conventional or manual control (see Chapter 4) via DCS or other types of control devices. In the Varenso K6 fullscale industrial boiler, most of the controls, especially in difficult challenging control situations, were previously done manually. Manual control is an effective method if the operators are well-trained and experienced. Using this background, it was decided to try to respond to the control challenges by using fuzzy logic. Since fuzzy logic is, according to several authors (see Chapter 4), a method where the manual control decisions and actions are possible to copy to the rule-base, it could be the suitable way to replace previous manual controls with automatic fuzzy control in a CFB boiler process as well.

The applications based on the existing control problems and control improvement consist of the following main packages:

- Steam pressure control,
- Compensation of the fuel quality fluctuation,
- Fuel-feed optimization,
- Increased bed fuel inventory monitoring.

5.1. Steam pressure control

Steam pressure control is typically the main control loop in a boiler. It is important and essential in the boiler control structure. The CFB boiler is not an exception. In the Varenso K6 case, the boiler is a swing boiler and controls the steam net pressure alone. The other boilers connected to the steam net are the recovery boiler, old bark boiler K4 and, occasionally, the oil-fired boiler K5 as a back up. This means that all load changes as well as the disturbances caused by the other boilers must be clarified by controlling the K6 fuel-feed. Steps in load changes can be very great though the steam net contains a steam accumulator. Daily practice has proven that even steps like steam flow rising from 35 kg/s to 55 kg/s and the reverse are relatively common. The maximum steam flow capacity is 60 kg/s.

Another big challenge for the steam pressure control is the nature of the fuel-feeding system and various fuels. The continuous fluctuation of the fuel heat value (see Fig. 36, Chapter 4) causes disturbances and non-stability to the steam pressure control. Most critical case is when the dry sod peat truck unloads to the silo and the sod peat starts to move into the combustion chamber from a waste fuel-feeding line. This means significant change to the firing rate and the steam pressure rises extremely rapidly because sod peat has two to three times higher heat value than the average waste fuel mix.

5.1.1 Control strategy

In the first phase, an effort was made to implement a steam flow-based pressure control where the PI-type FLC only corrected the power need set-point calculated from the amount of the steam flow. This kind of control structure was, however, too sensitive to measurement errors in steam flow which are very evident in the Varenso K6 boiler. Another reason why this kind of application did not work is that the steam flow-based pressure control has a better chance if the turbine controls the header pressure, unlike in the case of the K6 boiler.

An application was implemented where the steam pressure was controlled by a pressure-based fuzzy logic controller where the control output was corrected from steam flow change and steam pressure change derived term. The basic functions of the steam pressure controller are depicted in Figure 38.

5.1.2 The fuzzy logic controllers

For the PI-term of the controller an FLC was chosen consisting of rules of the form (see Chapter 3):

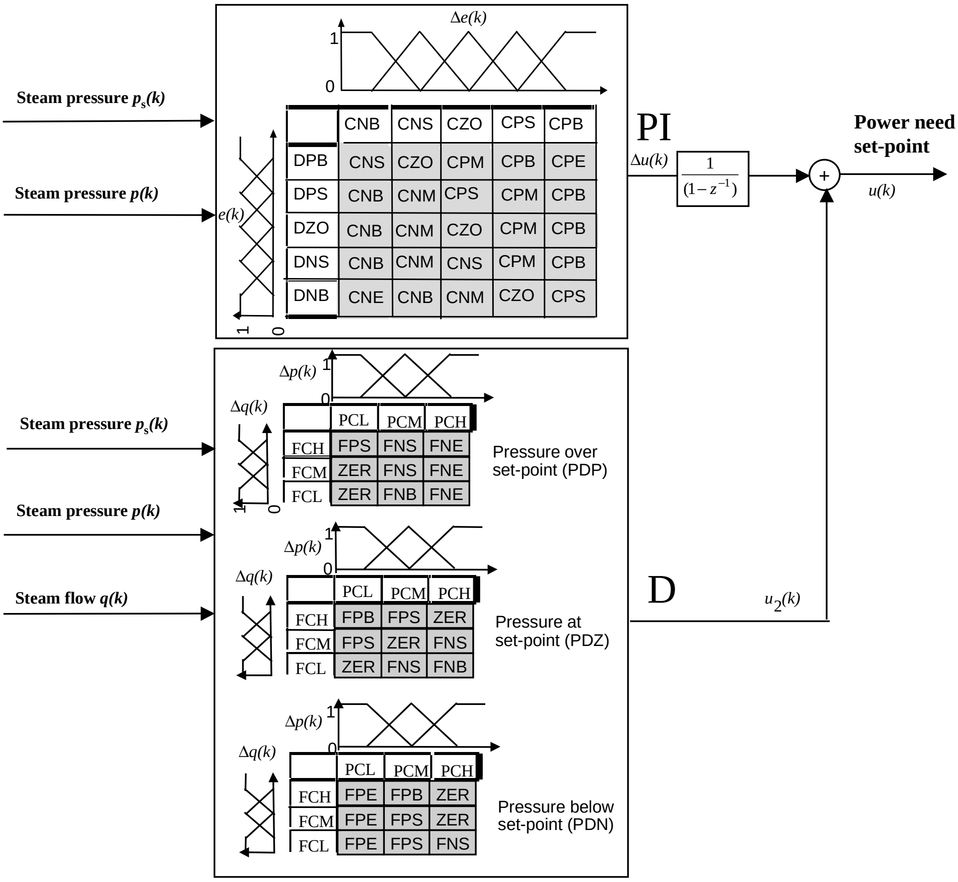
$$\text{if } e(k) \text{ is } \mathrm{F}_1^l \text{ and } \Delta e(k) \text{ is } \mathrm{F}_2^l \text{ then } \Delta u(k) \text{ is } \mathrm{G}^l, \tag{25}$$

where $e(k) = p_s(k) - p(k)$ is the error of steam pressure and $\Delta e(k) = e(k) - e(k-2)$ is the change of error and $\Delta u(k)$ is the change of control output.

For the D-term an FLC was chosen consisting of rules of the form:

$$\text{if } e(k) \text{ is } \mathrm{F}_1^l \text{ and } \Delta p(k) \text{ is } \mathrm{F}_2^l \text{ and } \Delta q(k) \text{ is } \mathrm{F}_3^l \text{ then } u_2 \text{ is } \mathrm{G}^l\,, \tag{26}$$

where $e(k) = p_s(k) - p(k)$ is the error of steam pressure and $\Delta p(k) = p(k) - p(k-1)$ is the change of steam pressure and $\Delta q(k) = q(k) - q(k-1)$ is the change of steam flow and u_2 is the control output.



	CNB	CNS	CZO	CPS	CPB
DPB	CNS	CZO	CPM	CPB	CPE
DPS	CNB	CNM	CPS	CPM	CPB
DZO	CNB	CNM	CZO	CPM	CPB
DNS	CNB	CNM	CNS	CPM	CPB
DNB	CNE	CNB	CNM	CZO	CPS

Pressure over set-point (PDP)

	PCL	PCM	PCH
FCH	FPS	FNS	FNE
FCM	ZER	FNS	FNE
FCL	ZER	FNB	FNE

Pressure at set-point (PDZ)

	PCL	PCM	PCH
FCH	FPB	FPS	ZER
FCM	FPS	ZER	FNS
FCL	ZER	FNS	FNB

Pressure below set-point (PDN)

	PCL	PCM	PCH
FCH	FPE	FPB	ZER
FCM	FPE	FPS	ZER
FCL	FPE	FPS	FNS

Fig. 38. The structure and rule-bases of the fuzzy steam pressure controller.

In Figure 38, following denotations are used:

For the error change of steam pressure ($\Delta e(k)$)

CPB	is error	change	positive big,
CPS	”	”	positive small,
CZO	”	”	zero,
CNS	”	”	negative small,
CNB	”	”	negative big,

and for the error of steam pressure ($e(k)$)

DPB is error	positive big,

DPS	”	positive small,
DZO	”	zero,
DNS	”	negative small,
DNB	”	negative big,

and for the output ($\Delta u(k)$)

CPE is control output change positive extremely big,
CPB is control output change positive big,
CPM is control output change positive medium,
CPS is control output change positive small,
CZO is control output change zero,
CNS is control output change negative small,
CNM is control output change negative medium,
CNB is control output change negative big,
CNE is control output change negative extremely big.

For the D-term respectively the change of steam flow ($\Delta q(k)$)

FCH is steam flow change positive,
FCM is steam flow change zero,
FCL is steam flow change negative,

and for the change of steam pressure ($\Delta p(k)$)

PCH is steam pressure change positive,
PCM is steam pressure change zero,
PCL is steam pressure change negative,

and for the error of steam pressure ($e(k)$)

PDP is steam pressure error positive,
PDZ is steam pressure error zero,
PDN is steam pressure error negative,

and for the output ($u_2(k)$)

FPE is set-point correction positive extremely big,
FPB is set-point correction positive big,
FPS is set-point correction positive small,
ZER is set-point correction zero,
FNS is set-point correction negative small,
FNB is set-point correction negative big,
FNE is set-point correction negative extremely big.

In the FLC controller, the error of steam pressure and change of error are fuzzified to five fuzzy sets by using triangular membership functions. The rule-base generated based on the knowledge of the process behavior is shown in Fig. 38. It is also acceptable to use three or seven fuzzy sets, but it was found that in most cases five sets is accurate enough. The fuzzification parameters defined after several tuning rounds are depicted in Figure 39.

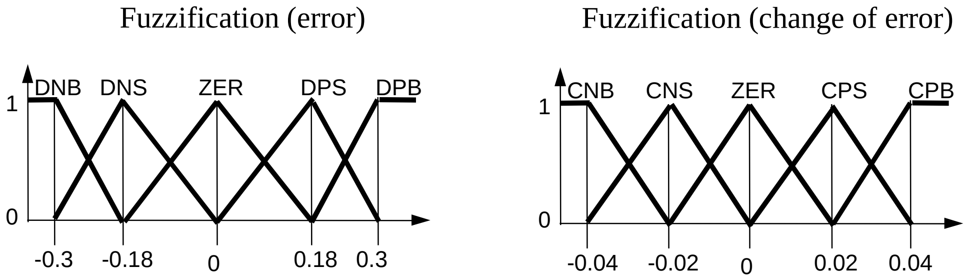


Fig. 39. The fuzzification parameters of the PI-term of the steam pressure controller.

The control output of the PI-term, which in this control loop is power need set-point (MW), is an incremental type and is continuously integrated with the previous output. The final adjustment to the controller's output is made by the D-term. The D-term was added because it helps the controller to respond faster to bigger load or fuel quality changes and the rule-base was constructed based on the operators' long experience of the boiler's and steam net's behavior. The fuzzification parameters (three fuzzy sets) are depicted in Figure 40.

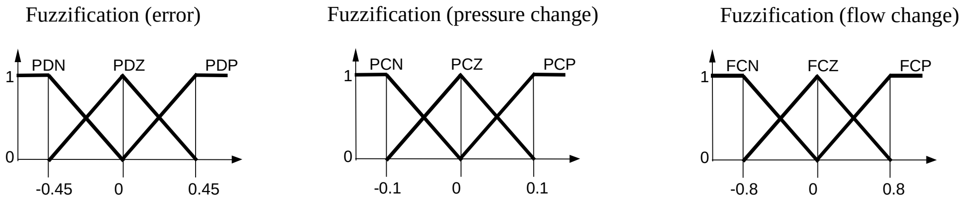


Fig. 40. The fuzzification parameters of the D-term of the steam pressure controller.

The D-term has a 3x3x3 rule-base (see Fig. 38), where the change of steam flow and change of steam pressure are combined with the error of steam pressure so that the simultaneous increase or decrease of the steam flow and the steam pressure are masked out. For example, if the steam pressure is near set-point, the control output is zero although the steam pressure and steam flow are both increasing. This is necessary because the increase of the steam pressure seems to cause an increase in steam flow without any real load change. This phenomena can be explained by the fact that the steam net and steam accumulator can store more steam when the pressure increases and the steam flow temporary increases although no steam consumption (load) change occurs.

The non-linear nature of the FLC is strongly utilized in steam pressure control (see Figs. 41, 42, 43 and 44) and it is mostly realized by defuzzification parameters. The extremely wide fuel variation fed through the same fuel (waste line) also includes fuels like sod peat, which has two to three times higher heat value than normal bark or mix of waste. Whenever the sod peat is fed to the boiler, the steam pressure rises dramatically (see Fig. 55, Chapter 6) in a very short time. The normal PID control is too slow to respond for varying process circumstances. The FLC, when tuned to strongly non-linear, showed better performance in difficult conditions. The main idea is to decrease the power need set-point very fast when the steam pressure indents to increase too high.

The steam pressure control showed best behavior when tuned to non-symmetric as depicted in Fig. 41. This means that control actions are stronger above than below the set-point though error is the same. This behavior can be explained by the energy capacity stored in the bed material and water/steam system.

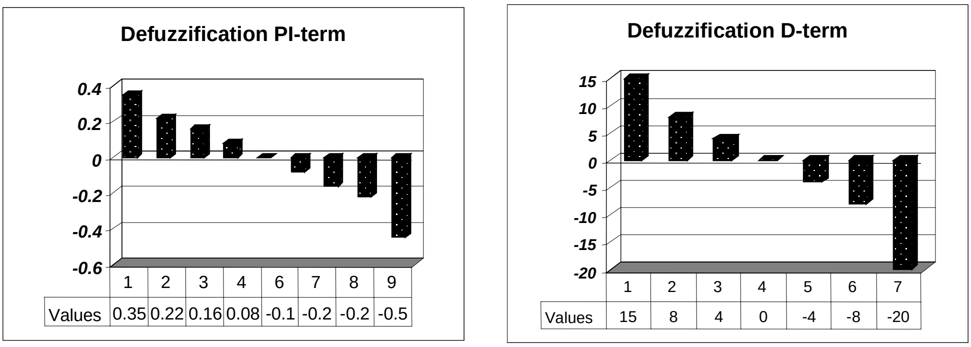


Fig. 41. The nine defuzzification parameters used in PI-term and the seven defuzzification parameters used in the D-term of the steam pressure controller.

The non-linearity as well as the non-symmetric structure can be seen from the 3-D control surfaces which are depicted for the PI-term in Fig. 42 and for the D-term in Fig. 43 and from Fig. 44, where the corresponding linearized parameters K_P and K_I are depicted in 3-D view. The non-linearity is stronger when the error is big while the controller is rather linear when measurement is close to set-point.

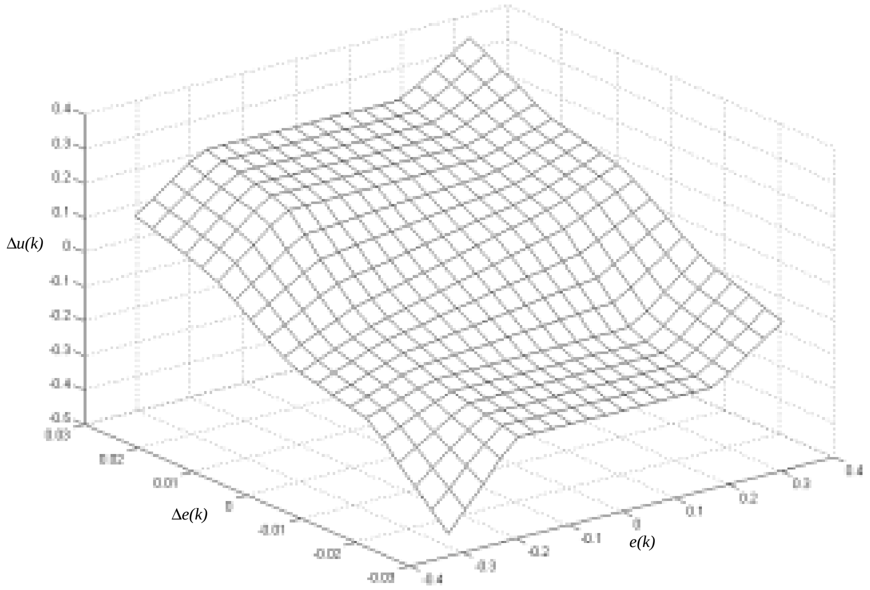


Fig. 42. The control surface of the PI-term in 3-D view.

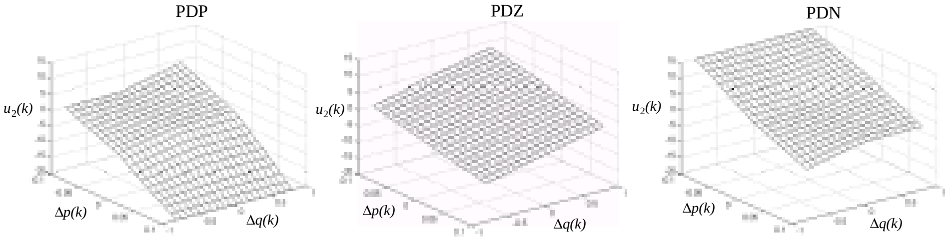


Fig. 43. The control surfaces of the D-term in 3-D view. The three cases depicted are the snapshots when the error of steam pressure obtains values of maximum (0.45), zero and minimum (-0.45).

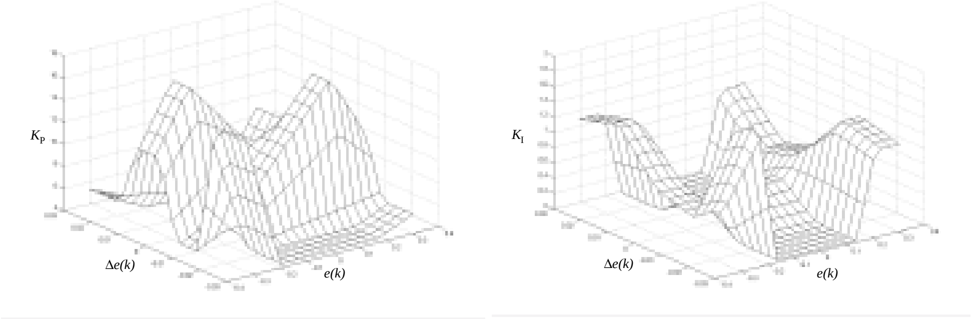


Fig. 44. The linearized parameters K_P and K_I of the PI-term of the controller in 3-D view. The K_P varies from 4.17 (min) to 16.47 (max) and the K_I from 0 (min) to 1.83 (max).

The execution cycle of the controller is 2 s which means that in practice the K_P variation is from 2.1 (min) to 8.2 (max) and K_I from 0 to 0.9 when it is compared with Varenso's conventional steam pressure PID controller which execution cycle is 1s. In the conventional controller the K_P slides from 2 to 5 and K_I from 0.0028 to 0.0067 depending on the bark/coal ratio and other fuel information given by the operator. According to Equation (24) given in Chapter 3, and by setting N_u =1, can be obtained that K_P ($N_{\Delta e}$) of the FLC varies inside the expected range (2,…,10). The K_I, correspondingly, seems not fit inside the range when compared with the conventional PID controller's tuning parameters.

Because the new control applications are located in the TP Alcont process control system, which is integrated with the older Alcont 1 system, an extra communication delay exists. It means that the power need set-point given by the FLC (executed in new TP Alcont) is updated using 5 s cycle to the Alcont 1 DCS system where the fuel-feed controllers are located. Correspondingly, the cycle time for measurement values update is 5 s. Shorter measurement update time would probably result in better performance, but in this case it was impossible to implement.

5.2. Compensation of the fuel quality fluctuation

The fuel mix burned in a multi-fuel CFB boiler can consist of fuels with varying heat value and moisture contents. This means that the total heat value of the waste fuel mass flow varies continuously. A more detailed discussion of this problem was given in Chapter 4.

The online measurement of the heat value and the moisture of the incoming fuel is very difficult or even impossible. Normally, the disturbing effect does not respond as feedback earlier until from the steam pressure.

During this research, a compensation structure for fuel heat value fluctuation, which tries to keep the combustion power constant by changing the fuel flow according to the burning conditions inside combustion chamber, was designed. The combustion power, also called firing rate, is the energy flux due to fuel that is combusting in the combustion chamber. The control implementation utilizes fuzzy logic control tools. The non-fuzzy ideas for a similar kind of control structure are discussed by several authors like Ikonen (1994), Ryd (1994), Åström *et al.* (1993), Ikonen & Kotajärvi (1993), Henttonen *et al.* (1992) and Kortela *et al.* (1991).

5.2.1. Control strategy

In the suggested application, the fuzzy logic controller corrects the estimated heat value of the waste fuel and the fuel-feed optimizing system decreases or increases the mass flow of the waste fuel correspondingly to the heat value changes.

The fuzzy compensation of the fuel quality is integrated to a fuel-feed optimization system as depicted in Fig. 45. This application package uses the fuzzy logic controller as a steam pressure or boiler load controller, which was described earlier in this chapter. The second fuzzy logic controller compensates the disturbances caused by continuous fluctuating fuel mix feed. Finally, the feed set-points for different fuel-feeders are given by the optimizing system.

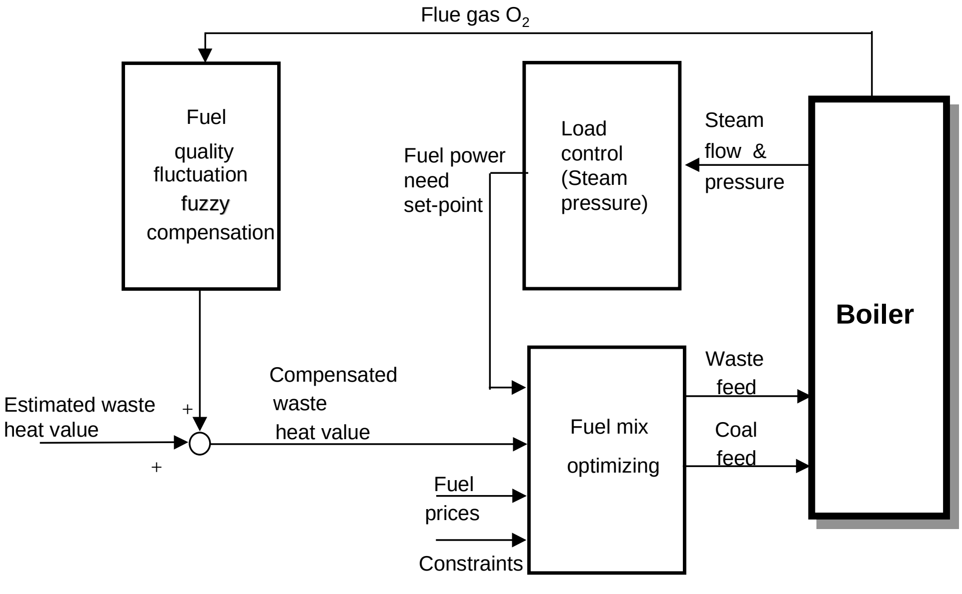


Fig. 45. The function principle of the application containing the steam pressure controller, the compensation of the fuel quality fluctuation and the fuel-feed optimization.

5.2.2. Fuzzy logic controller

The fuzzy logic controller implemented was based on the measurement of flue gas oxygen content from the combustion chamber. For the controller, an FLC was chosen consisting of rules of the form (see Chapter 3):

$$\text{if } e(k) \text{ is } \mathrm{F}_1^l \text{ and } \Delta e(k) \text{ is } \mathrm{F}_2^l \text{ then } \Delta u(k) \text{ is } \mathrm{G}^l, \qquad (27)$$

where $e(k) = o_s(k) - o(k)$ is the error of flue gas O_2 and $\Delta e(k) = e(k) - e(k-2)$ is the change of error and $\Delta u(k)$ is the change of control output which is incremental type and is continuously summarized with previous outputs.

In the test version used in the Karhula pilot plant the form used was:

$$\text{if } e(k) \text{ is } \mathrm{F}_1^l \text{ and } \Delta e(k) \text{ is } \mathrm{F}_2^l \text{ then } u(k) \text{ is } \mathrm{G}^l, \qquad (28)$$

where $e(k) = o_s(k) - o(k)$ is the error of flue gas O_2 and $\Delta e(k) = e(k) - e(k-2)$ is the change of error and $u(k)$ is the control output.

In the fuzzification phase, these terms are fuzzified to five fuzzy sets by using triangular membership functions. The fuzzification parameters used in Varenso K6 are depicted in Fig. 46 and the parameters used in the Karhula pilot plant in Fig. 47 respectively. In both cases, the fuzzification parameters as well as the defuzzification parameters were defined based on the operators' and automation technicians' experience and expertise.

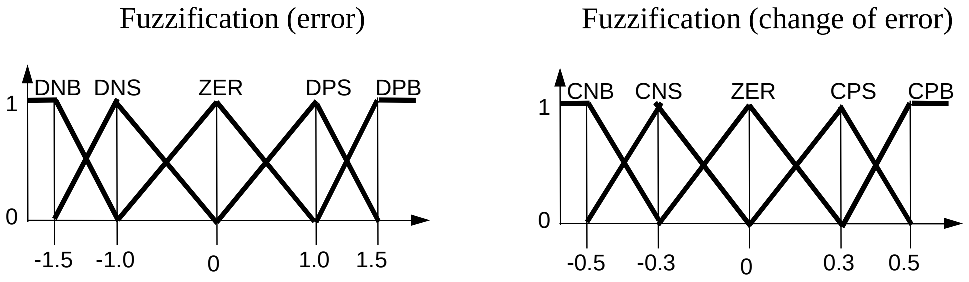
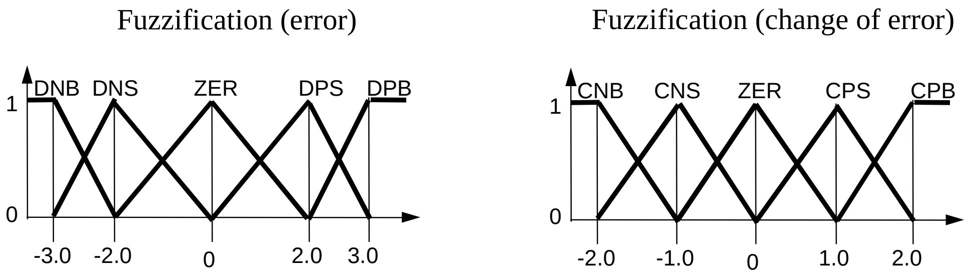


Fig. 46. The fuzzification parameters used in fuel quality fluctuation control at Varenso K6.

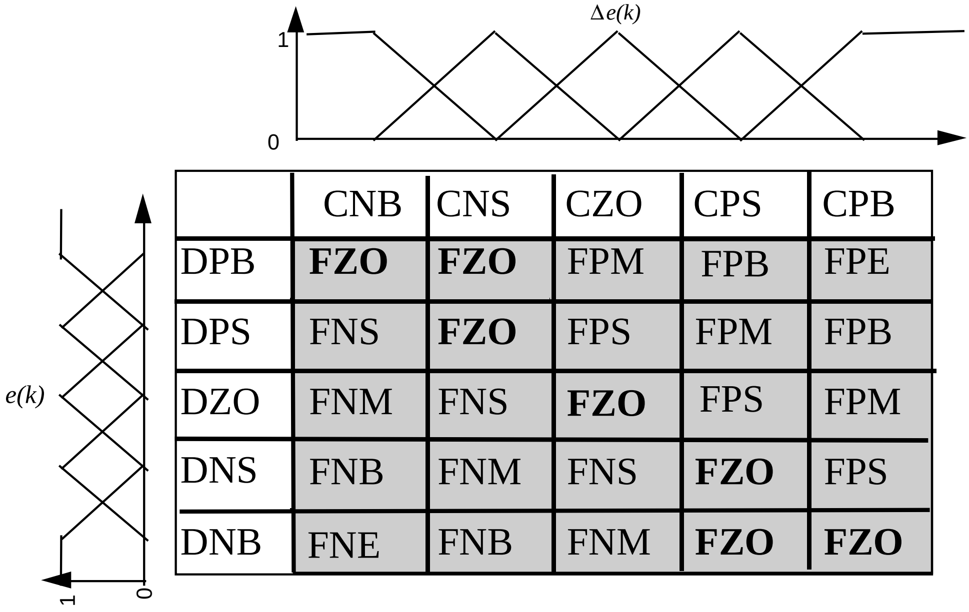

Fuzzification (error)

Fuzzification (change of error)

Fig. 47. The fuzzification parameters used in fuel quality fluctuation control at Karhula pilot plant.

As shown in Figures 46 and 47, the tuning of the controller was different in the Karhula pilot plant. Main reason for that was the pilot plant boiler is much smaller and the changes of the combustion process are faster, and the responses more sensitive compared to a big, fullscale boiler.

The FLC rule-base derived can be written as shown in Figure 48.



	CNB	CNS	CZO	CPS	CPB
DPB	**FZO**	**FZO**	FPM	FPB	FPE
DPS	FNS	**FZO**	FPS	FPM	FPB
DZO	FNM	FNS	**FZO**	FPS	FPM
DNS	FNB	FNM	FNS	**FZO**	FPS
DNB	FNE	FNB	FNM	**FZO**	**FZO**

Fig. 48. The rule-base of the fuzzy logic compensation controller of the fuel quality fluctuation.

In Figure 48, following denotations are used:

For the error change of flue gas O_2 ($\Delta e(k)$)

CPB	is error	change	positive big,
CPS	”	”	positive small,
CZO	”	”	zero,
CNS	”	”	negative small,
CNB	”	”	negative big,

and for the error of flue gas O_2 ($e(k)$)

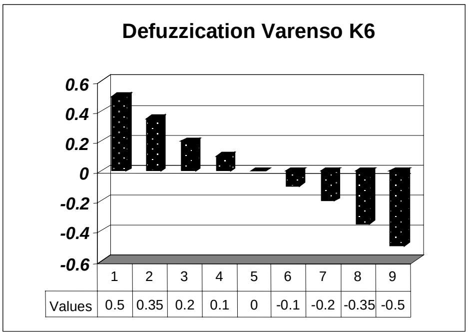
DPB	is error	positive big,
DPS	”	positive small,
DZO	”	zero,
DNS	”	negative small,
DNB	”	negative big,

and for the output ($\Delta u(k)$)

FPE is waste heat value correction positive extremely big,
FPB is waste heat value correction positive big,
FPM is waste heat value correction positive medium,
FPS is waste heat value correction positive small,
FZO is waste heat value correction zero,
FNS is waste heat value correction negative small,
FNM is waste heat value correction negative medium,
FNB is waste heat value correction negative big,
FNE is waste heat value correction negative extremely big.

Output, like FPE, is a correction term which corrects the estimated (fixed) heat value of the waste fuel. For example, when the flue gas oxygen content increases, the controller decreases the waste fuel heat value and, in the case of decreasing oxygen content, the heat value increases. Maximum correction is ±15 %. The heat value of the waste fuel as well as the coal heat value are connected to the optimizing procedure. The feed set-points for waste and coal feed are given by the optimizing system, which follows the set-point of the power need from the steam pressure controller.

The defuzzification parameters used both in Varenso K6 and in the Karhula pilot plant are shown in Fig. 49. The large difference is caused by the fact that in Karhula the correction went directly to the waste heat value as percents, but in Varenso it was more relevant to use incremental type of output with an integrator.



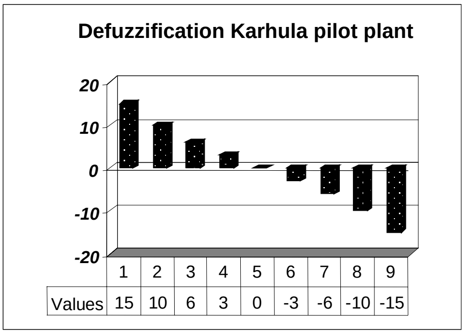


Fig. 49. The nine defuzzification parameters of the fuel quality fluctuation compensation. Left are parameters used in Varenso K6 and right are parameters used in the Karhula pilot plant.

The aggregation operator used in the fuzzy logic controller is an algebraic product. An algebraic product as an aggregation operator typically forms a smooth control surface. The control surface for the example rule-base is depicted in Fig. 50. The 3-D views for linearized parameters K_P and K_I are depicted in Fig. 51 respectively.

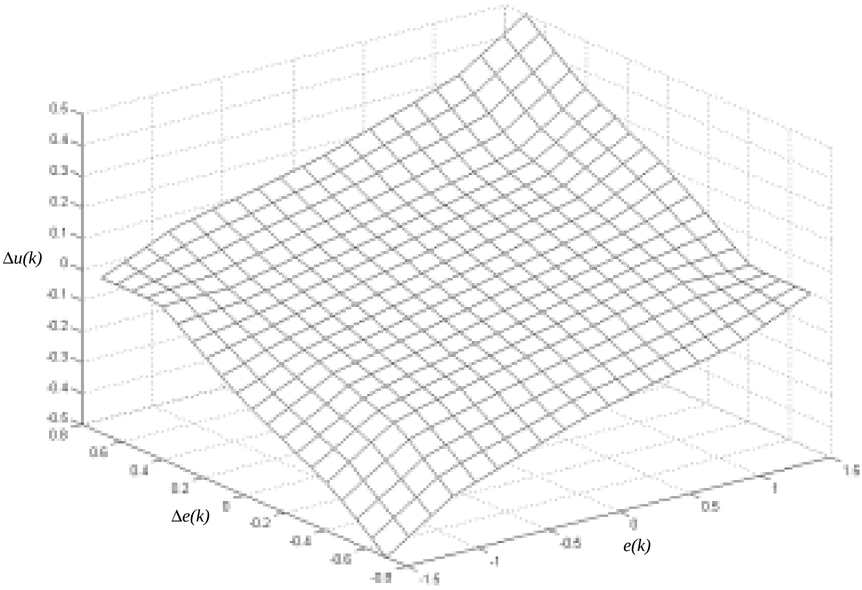


Fig. 50. The control surface of the fuzzy PI controller used in Varenso K6 boiler in a 3-D view.

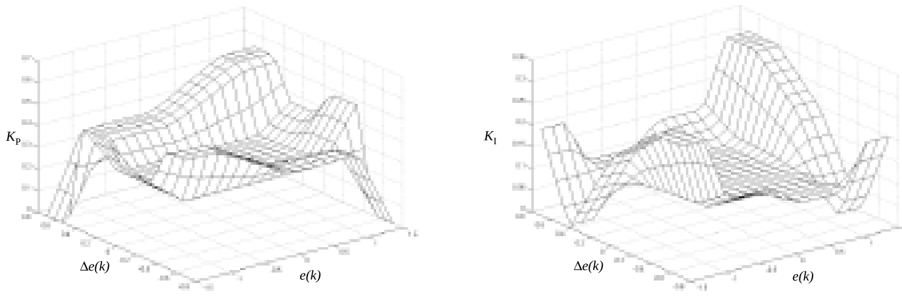


Fig. 51. The linearized parameters K_P and K_I of the PI controller in 3-D view. The K_P varies from 0 (min) to 0.54 (max) and the K_I from 0.007 (min) to 0.30 (max).

The execution cycle of the compensation application is 5 s, which was shown to be sufficient. The comparison of the tuning parameters K_P and K_I with the conventional PID controller is not possible to do because at the Varenso K6 boiler there were not any similar kind of control structures until the FLC implementation.

As mentioned before, the new control applications are located in TP Alcont process control system which is integrated with the older Alcont 1 system so an extra communication delay exists. It means that the cycle time for measurement values update is also 5 s.

5.3. Fuel-feed optimization

The fuel-feed optimization itself does not include any fuzzy functions but, because it is the essential term of the closed fuel-feed control loop it is introduced in more detail below. The function of the optimizing system is to resolve settings for the waste feed and coal feed so that the heat value contents of the total feed equals the power set-point and the price per unit time for the total feed is at its minimum. Thus the closed loop dynamic control optimization implements the required power input with the lowest cost within constraints.

5.3.1. Optimization procedure

The fuel-feed optimization connected with the steam pressure or power need controller (see Fig. 45) receives the required fuel power as an input of a set-point nature. Other inputs to the optimization are:

- Estimated (fixed) heat value in megawatts per kilogram for the waste fuel, and the same for coal as a known constant,
- Prices per kilogram for the waste fuel and coal.

The function of the optimization is to resolve settings for the waste feed and coal feed such as:

- The heat value contents of the total feed equals the fuel power set-point,
- The price per unit time for the total feed is at its minimum.

Optimization itself is quite a simple minimization of the cost-based objective function which, in this case, means minimization of energy price produced and can be written as:

$$\min_{x_1,x_2} a_1 x_1(k) + a_2 x_2(k) \tag{29}$$

subject to constraints

$$
\begin{aligned}
&x_{\max,1}(k) \geq x_1(k)\\
&x_{\max,2}(k) \geq x_2(k)\\
&x_1(k) \geq x_{\min,1}(k)\\
&x_2(k) \geq x_{\min,2}(k)\\
&b_1 x_1(k) + b_2(k) x_2(k) = S,
\end{aligned}
$$

where:

a_1 is coal price [FIM/kg],
a_2 is waste fuel price [FIM/kg],
x_1 is coal flow [kg/s],
x_2 is waste fuel flow [kg/s],
b_1 is coal heat value [MW/kg],
b_2 is waste fuel heat value [MW/kg],
S is power need set-point given by the steam pressure controller [MW/s].

5.3.2. Used constraints

The constraints used can be divided to three categories, which are:

- Less than or equal to,
- Greater than or equal to,
- Equal to.

"Less than or equal to" constraints limit the waste fuel and coal feed continuously and are changing depending on the process status. Naturally, the maximum capacity of the feeding lines is the basic limitation, but process operators can change, for example, the waste fuel maximum to smaller than maximum in order to feed more coal. These kinds of situations can be lack of waste fuel or very bad quality of the waste fuel. For security reasons, the maximum coal feed in Varenso K6 boiler was limited to 6 kg/s.

"Greater than or equal to" constraints for both coal and waste fuel are 0 kg/s, except when process status demands that the constraints are changed. These kinds of cases are disturbances like fuel silo bridging, fuel trip, flue gas fan capacity limitation or too low bed temperature when coal feed is forced to be greater than zero, and replacing part of missing or very low grade waste fuel flow. This means that coal is fed because of process demands even if the optimization will not do it due to more expensive energy cost.

The only, but important, "Equal to" constraint is the power need which must be continuously fulfilled or optimization error will occur. This major constraint simply sets the power set-point. The optimization only divides the power need to be fulfilled by separate fuels (coal and waste fuel) which practically means setting the coal/waste fuel ratio.

Assuming that coal price is higher than waste fuel price ($a_1>a_2$) as the case normally is, then if $(b_1 x_{\min,1}(k)+b_2(k)x_{\max,2}(k))\geq S(k)$:

$$x_1(k)=x_{\min,1}(k),\;\; x_2(k)=\frac{S(k)-b_1 x_{\min,1}(k)}{b_2(k)}, \tag{30}$$

otherwise:

$$x_1(k)=\frac{S(k)-b_2(k)x_{\max,2}(k)}{b_1},\;\; x_2(k)=x_{\max,2}(k). \tag{31}$$

This means that coal feed is always at lower constraint (0 kg/s) if the power need can be fulfilled by waste. In the case when the waste fuel-feed can not fulfill the power need, the coal feed is started. A graphical solution for this optimization case is depicted in Fig. 52. In practice, the coal feed is started and added step-wise so that actual steam pressure control is always done by waste fuel-feed, and the base fuel power is done by coal when coal is needed.

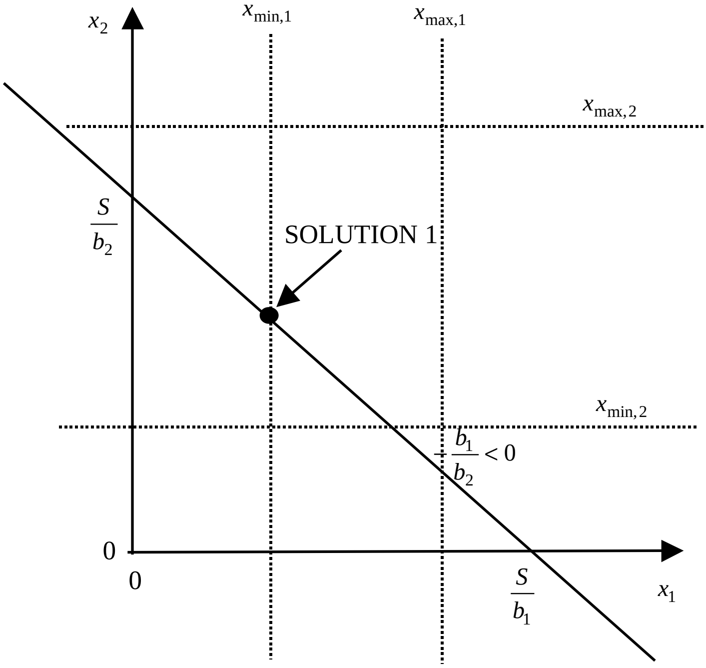


Fig. 52. A graphical solution of the fuel-feed optimization problem. Solution 1 represents the case when the base fuel power is done by coal and the needed control actions will be done by waste.

Due to fact that waste fuel is normally considered to be cheaper than coal and because the waste is always kept as the control fuel, the optimization carries out the formula in Equation 30. If the fuel quality compensation controller is combined, the optimization can be obtained:

$$x_2(k) = \frac{1}{b_2(k)}\left[S(k) - b_1 x_{\min,1}(k)\right]. \tag{32}$$

5.4. Interaction of the steam pressure control, fuel quality compensation and O$_2$ trim

The steam pressure controller, fuel quality compensation controller and oxygen content controller (O$_2$ trim) form a control block where fuel power and O$_2$ are controlled by fuel-feed rate and combustion (secondary) air. This kind of structure can lead to oscillations if the controllers are not tuned in different frequency bands, and especially because the controllers have integrator term.

The main idea behind the control structure is that the fuel quality compensation is the fastest loop, which compensates the fuel quality disturbances by correcting the fixed estimated average waste fuel heat value maximum correction being ± 15 % of the fixed heat value. The waste fuel heat value correction is based on the combustion results, i.e. flue gas O_2 content, which is the fastest feedback from the combustion process. The controller is designed to allow O_2 variation around the set-point without any greater action (see Fig. 51), but output is getting stronger when the error increases which indicates that the fuel quality change is obvious. The tuning parameters for the controller were K_P (0…0.54) and K_I (0.007…0.3), execution cycle time being 5 s.

The steam pressure controller controls the fuel-feed rate according to steam pressure and steam flow process values. The interaction with fuel quality compensation takes place in optimization where the fuel-feed rate set-point is set according to power need and fuel heat values of waste and coal (see discussion above). In practice, the waste fuel-feed is increased (heat value worsened) when the flue gas O_2 increases and decreases in opposing cases respectively. While the waste fuel heat value is changed, similar correction is done for combustion air feed in order to mask out the false air feed because air feed is based on fuel mass flow. The tuning parameters for the PI-term of controller were K_P (4.17…16.47) and K_I (0…1.83) (see Fig. 44), execution cycle time being 2s.

The O_2 trim is realized with two controllers (based on left or right O_2 and were tuned to be rather slow with K_P (0.7 if right or 0,5 if left), K_I (0.00417 if right and 0.00208 if right) and K_D (0). The active controller is selected based on the minimum O_2 measurement.

In practice, the fuel quality compensation and O_2 trim seemed not to disturb each other and the O_2 trim did not drift to the limit more often than without fuel quality compensation. The waste fuel heat value correction also rather seldomly reaches upper or lower limit. This is mainly caused by the continuous changes of the fuel quality so that system is always under change. For example, if the fuel quality change has a very short residence time it will be compensated totally by fuel quality compensator alone and the O_2 trim should not react. If the O_2 error tends to be more continuous, the O_2 trim naturally tries to control the oxygen level by changing the secondary air flow. In the case of hitting the control limits (O_2 trim), the fuel-feed is limited and the operator must change the air coefficient which has direct a influence on the amount of fed air per fuel mass flow.

5.5. Increased fuel inventory monitoring

To find out when the excess fuel (char) in the bed is increasing too fast, an application was developed which is based on fuzzy decision-making. The bed fuel inventory has been discussed by authors like Ikonen (1994), Åström *et al.* (1993), Ikonen & Kotajärvi (1993), and Kortela *et al.* (1991). Because the basic idea for this thesis was to use a fuzzy logic approach instead of a more or less accurate bed fuel inventory, only the case of the temporary dramatically increased coal (char) inventory was the main control problem; the previous although very interesting research work was mostly ignored.

Ten different inputs from the process were fuzzified either to three or five membership functions. The inputs used in decision-making (see Fig. 53) come from fuel-feed changes, bed circumstances, steam production and flue gas.

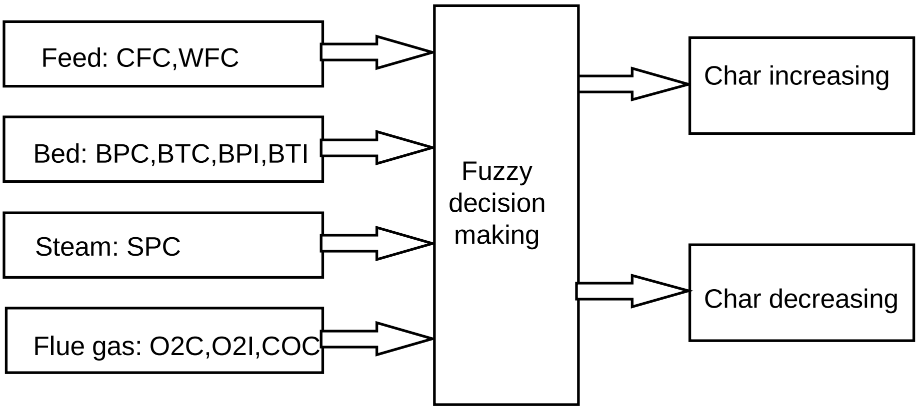


Fig. 53. The structure of the bed fuel inventory monitoring system.

5.5.1 Decision-making logic

The decision-making of the bed fuel inventory is possible to build up following several different structures. One simple structure is proposed below.

For increasing bed fuel inventory it can be written:

IF
CFC (Coal Feed Change) is positive)
AND
BPC (Bed Pressure Change) is positive
OR
BTC (Bed Temperature Change) is not positive
AND
BTC (Bed Temperature Change) is not positive
OR
SPC (Steam Pressure Change) is not positive
AND
SPC (Steam Pressure Change) is not positive big
AND
O2C (Flue Gas O_2 Change) is not negative

OR
COC (Flue Gas CO Change) is positive

THEN bed fuel inventory increases.

For decreasing bed fuel inventory it can be written:

IF
CFC (Coal Feed Change) is zero
OR
CFC (Coal Feed Change) is negative
AND
WFC (Waste Fuel-feed Change) is zero
OR
WFC (Waste Fuel-feed Change) is negative
AND
BPI (Bed Pressure) is high
OR
BPI (Bed Pressure) is normal
AND
BTI (Bed Temperature) is high
AND
O2I (Flue Gas O_2) is high
OR
O2I (Flue Gas O_2)is normal

THEN bed fuel inventory decreases.

As mentioned earlier, the only significance of this decision-making is to notice cases when the coal is fed too much into the combustion chamber and is indicated as increased fuel inventory. For instance, when the coal feed is high and bed temperature is not rising, and the steam pressure is not increasing and flue gas analysis indicates that combustion is not complete, the risk of increased fuel inventory is obvious, especially if this kind of situation lasts too long. The normal situation, when the combustion process in equilibrium, is called decreasing bed inventory. Thus, by increased or decreased bed inventory in this thesis, estimating exact amounts of char in the bed were not tried.

The rule-base was realized by using MIN and MAX operators (AND & OR). In practice, both logic (increasing and decreasing) add or subtract integrator value on every execution cycle. The integrator is limited to bigger than zero so it can not get negative values, though char is decreasing continuously. Finally, the integrator value was fuzzified in order to get values for CIB (see Fig. 64, Chapter 6) from 0 to 1. The execution cycle used in decision-making was 1s, although longer execution cycle would be sufficient as well.

The fuzzification parameters are not introduced because they depend on the boiler and do include less interest while the main interest focus on the decision-making logic itself.

The result of the bed fuel inventory monitoring was utilized as combustion performance indication and in sintering threat monitoring.

6. Industrial experiments and discussion

In the first part of this chapter, the experiments completed in the Foster Wheeler Research Center in Karhula and the test runs made with the fullscale application in the Varenso 150 MW(th) CFB boiler K6 are briefly introduced. The second part of the chapter is devoted to the results of those four applications detailed in Chapter 5.

Together with each application, the results of the fuzzy logic applications implemented and tested are discussed. The results from both boilers (Karhula and Varenso) are introduced and discussed if available. However, the limitations of the pilot plant and process as well as data recording limitations in Varenso caused the discussion of the applications to not be all-inclusive.

6.1. Experiments made in 2 MW(e) CFB pilot plant boiler

The boiler used in the Karhula Reseach Center is a 2 MW(e) CFB pilot plant (see Chapter 2). The fuzzy applications were implemented in the **TotalPlant®** Alcont system, which is integrated with the older (Alcont 1) DCS system.

Thirty-four different experiments were carried out (excluding preliminary tests) in two experiment periods during the course of December 1996 - March 1997. Typical experiments were steps in fuel-feed quality demonstrated by very dry or very wet and icy portions added into the fuel-feed. Oil was added to the bark to improve the heat value. The fuel trip simulations and coal feed step experiments were included in the experiment program. A detailed experiment program is shown in Tables 6 and 7.

Table 6. The experiments made during the first experiment period.

DATE	TIME hh:mm	NAME
1. Thu. 12.12.1996	22:33-00:35	BARK 1
2. Fri. 13.12.1996	00:38-01:50	CASCADE 1
3. Fri. 13.12.1996	02:36-03:.30	CASCADE 2
4. Fri. 13.12.1996	03:45-05:30	FUEL Q CHA. 1
5. Fri. 13.12.1996	08:52-10:05	BARK 2
6. Fri. 13.12.1996	15:15-15:45	FUEL Q CHA. 2
7. Fri. 13.12.1996	15:50-16:29	CASCADE 3
8. Fri. 13.12.1996	16:43-17:05	BREAK 1
9. Fri. 13.12.1996	17:10-17:25	BREAK 2
10.Fri. 13.12.1996	17:32-17:44	BREAK 3
11.Fri. 13.12.1996	22:33-00:35	FUEL Q CHA. 3

Table 7. The experiments made during the second experiment period

DATE	TIME	NAME
1. Thu. 13.03.1997	18:15-18:59	STARTING
2. Thu. 13.03.1997	18:59-19:03	COMPENS. 1
3. Thu. 13.03.1997	19:28-20:45	COMPENS. 2
4. Thu. 13.03.1997	21:15-22:19	COMPENS. 3
5. Thu. 13.03.1997	22:19-22:45	COMPENS .4
6. Thu. 13.03.1997	23:10-23:30	COMPENS. 5
7. Fri. 14.03.1997	09:30-09:42	COMPENS. 6
8. Fri. 14.03.1997	14:13-14:22	BREAK 1
9. Fri. 14.03.1997	14:24-14:44	OPTIM 1
10.Fri. 14.03.1997	14:44-14:57	SUPPORT 1
11.Fri. 14.03.1997	15:18-15:27	SUPPORT 2
12.Fri. 14.3.1997	15:51-16:15	LOAD 1
13.Fri. 14.3.1997	16:42-17:28	SINTR 1
14.Fri. 21.3.1997	14:35-14:49	COMPENS. 7
15.Fri. 21.3.1997	14:56-15:30	COMPENS. 8
16.Fri. 21.3.1997	15:30-15:41	COMPENS .9
17.Fri. 21.3.1997	15:41-16:00	COMPENS. 10
18.Fri. 21.3.1997	16.:4-16:31	COMPENS. 11
19.Fri. 21.3.1997	16:31-16:50	COMPENS. 12
20.Fri. 21.3.1997	18:01-18:24	COMPENS. 13
21.Fri. 21.3.1997	18:24-18:43	COMPENS. 14
22.Fri. 21.3.1997	19:02-19:29	COMPENS. 15
23.Fri. 21.3.1997	19:34-19:50	COMPENS. 16

Fuels were transported from the Varenso mill to Karhula to ensure that at least partly similar fuels to those used in the industrial boiler would be used in the experiments. The main fuel used was bark. For fuel quality fluctuation simulation, dry cutter chips were used as a high quality fuel.

The parametrizing of the fuzzy controllers and the decision chains were made together with the pilot plant’s technicians and operators by interviews. Their opinion to what is a big process value change and what is the high process value, or low process value in each case in the boiler were asked and recorded.

The main goal of the experiments in Karhula was to test developed applications, implement them to a boiler and also become familiar with the test boiler and try to understand more about the dynamics and control of the CFB boiler.

As one can see from Tables 6 and 7, the experiments were rather short. The main reason for that was limited time period when the pilot plant was available for these experiments and problems with the bark feeding system which caused many difficulties and time lost in the first experiment period. Still, the most important experiments were accomplished. The second experiment period was more successful and most of the existing applications managed to be tested.

Altogether, the experiment periods in the Karhula pilot plant boiler provided much information on the dynamics, and also a bit of experience on how to use FLC control methods in controlling the circulating fluidized bed boiler. The safe, but still very realistic, environment in the pilot plant offered a good environment for new inventions and suggestions for improvements. Although it had good performance, the small boiler with the narrow bed set limitations to the experiment program because the bed circumstances are quite ideal compared to a fullscale industrial boiler with a much larger bed area.

The new fuzzy applications showed their suitability to control the challenging control loops as expected in the multi-fuel CFB boiler. As mentioned above, it was not possible to test all the applications planned, but the experiments gave a good preliminary view to the control challenges in the industrial size boiler.

6.2. Test runs made in 150 MW(th) industrial CFB boiler

As mentioned several times, the Varenso K6 boiler has a very critical role in the mill steam production. Based on that fact, no extra experiments were allowed to be made during and after the implementation period.

In order to be able to get data from the control results, it was possible to just record the data available and compare the results using longer periods before and after implementation of the new fuzzy applications. The data used for result analysis was recorded during the entire Weeks 45, 48 and 49 in 1997, and during the entire Weeks 12 and 13 in 1998. In this Chapter, the analysis is mostly based on examples printed from those weeks. A complete printout of the essential results are gathered in APPENDIX 1.

The results from industrial boiler were recorded by using an existing data recorder. The process values defined to the data collection is available at the shortest as only three minute averages.

The result analysis used based on one week data (before and after the FLC implementation) was chosen because one week is a period long enough to average most of the continuous disturbances caused by several fuel, load and steam net problems, which are an every day reality in a boiler like Varenso K6. Some shorter period samples for controller performance monitoring are also used.

During the test period in the Varenso mill, all the control loops depicted in Fig. 45 in Chapter 5 (steam pressure controller, compensation of the fuel quality fluctuation and fuel-feed optimization) were at all times simultaneously running. This was effected by the interlocking system used in the Varenso K6 boiler, which forced all the advanced control loops to be on if any part of the advanced system wanted to be used for control.

The applications used in the Varenso K6 were derived from the applications used in the Karhula experiments. The biggest change was made in steam pressure control as discussed in Chapter 5. The compensation of the fuel quality fluctuation remained rather similar except the defuzzification parameters had to be changed; This too was shown in Chapter 5. Fuel-feed optimization procedure was similar in Karhula and Varenso but the structure of dynamic constraints in the industrial boiler differ a lot from those in the pilot plant. The structure of the increased fuel inventory monitoring logic remained the same but, naturally, re-tuning was necessary.

6.3. Steam pressure control

6.3.1. Karhula pilot plant

The fuzzy steam pressure controller was impossible to test reliably in the pilot plant since it needs steam pressure and steam flow as inputs. In the pilot plant boiler, the water was only heated, not vaporized to steam, and one could only simulate those inputs from water temperature change and flow. Based on these facts, the results of the experiment made in Karhula are ignored.

6.3.2. Varenso K6

Steam pressure was surely the most closely watched process value during the FLC implementations. This sensitive measurement tells much about combustion performance and also the success of the boiler control.

The Varenso K6 industrial boiler, as mentioned several times in this thesis, is very difficult to control because of many kinds of disturbances. Not only the normal load changes from the steam consumers but also all kind of steam net disturbances and multi-fuel operation make the control structure rather challenging.

Figure 54 illustrates the histograms printed from one week's data of steam pressure before and after the FLC implementation. The data depicted is recorded during Week 13 after the FLC implementation in 1998 and the reference week is Week 48 in 1997.

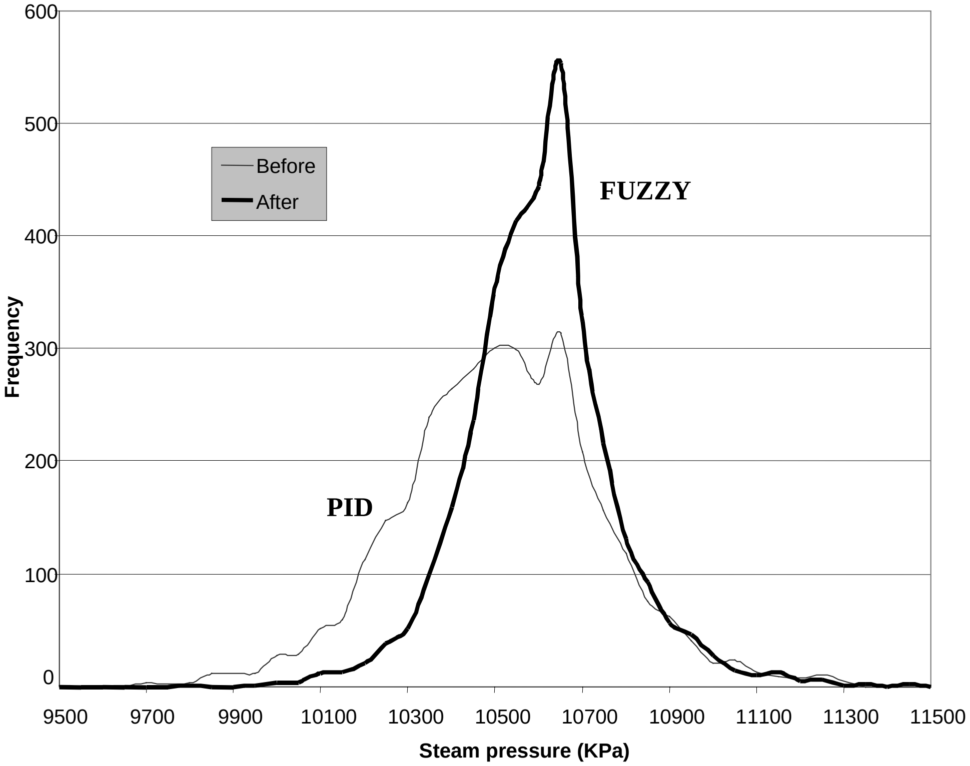


Fig. 54. Steam pressure histograms before and after the FLC implementations.

In Figures 55 and 56 the performance of the steam pressure controller when sod peat was fed to the boiler are depicted. In Figure 55, the response is coming from the PID controller and the usage of coal feed is decided “manually”, which means that the operator starts the coal feed manually but can set the coal feeder to cascade mode to follow power need set-point. The peaks downwards in O_2 measurements indicate sod peat pulses to the boiler. The sod peat truck was clocked in to the power plant at 04:37:00 hours and usually starts unloading some minutes after that.

The timing when the first batches of sod peat are introduced to the boiler depends on the existing amount of fuel in the waste fuel silos, but typically varies between 10 minutes to one hour. The previous sod peat truck was clocked in at 01:50:00 hours and would probably still be causing disturbances between 03:30 and 04:30.

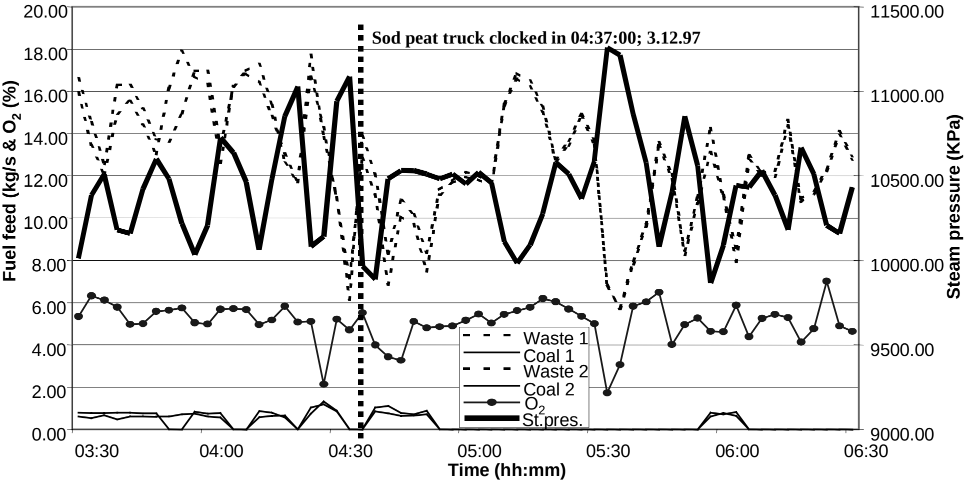


Fig. 55. Steam pressure, flue gas O_2 and fuel-feed recorded 3.12.1997 (Week 49/98) before the FLC implementation.

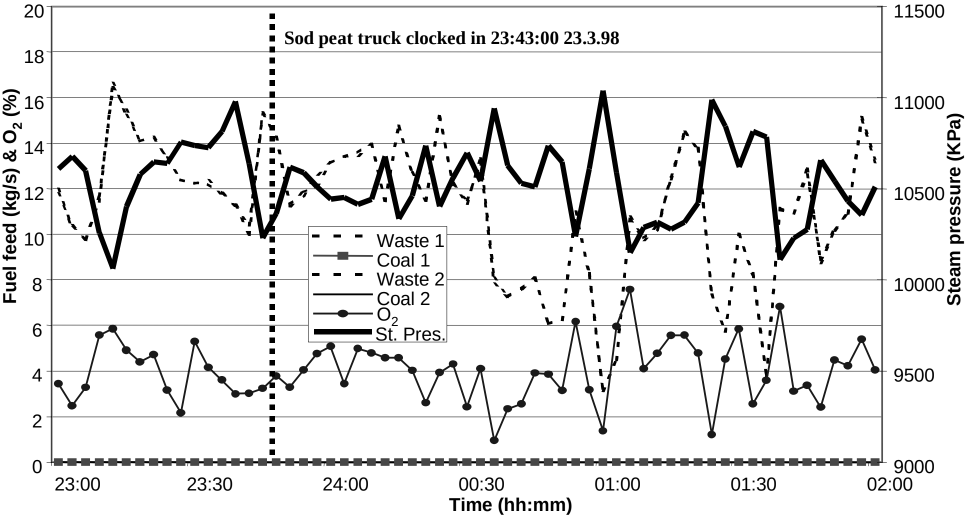


Fig. 56. Steam pressure, flue gas O_2 and fuel-feed recorded 23-24.3.1998 (Week 13/98) after the FLC implementation.

In Figure 56, the response is coming from the FLC controller and the usage of coal feed is decided by the optimization procedure, which means that the coal is not used at all. The peaks downwards in O_2 measurements indicate sod peat pulses to the boiler. The sod peat truck was clocked into the power plant at 23:43:00 hours, and the previous sod peat truck was clocked in at 09:33:00 hours. So the previous batch of sod peat is surely not shown in the waste fuel mix.

In Figure 57, the corresponding steam flows during the sod peat combustion periods depicted in Figs. 55 and 56 are shown. These examples were chosen because the load does not take major steps and is nearly at the same level during the both studied periods.

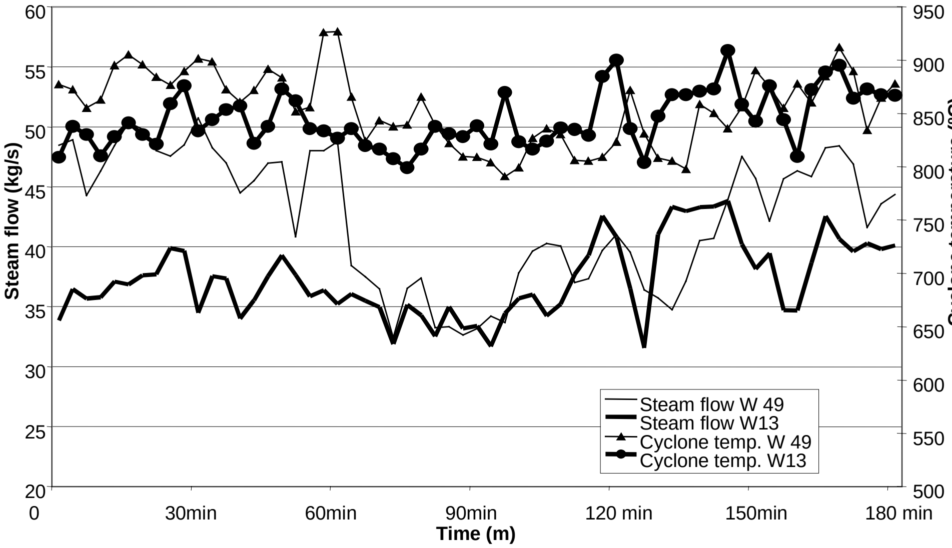


Fig. 57. The steam flow and cyclone temperature during the test period depicted in Figs. 55 and 56.

6.3.3. Discussion

In a process such as the Varenso K6 boiler, the behavior of the steam pressure controller is critical to the total power block performance. Disturbances like non-homogeneous, low grade fuel and load changes must be handled so that the steam consumers are not affected. The most difficult cases like the paper machine trips and start-ups must be clarified. The steam net system includes a steam accumulator but it can not dampen the load changes satisfactorily and its control strategy needs to be redesigned in order to reach better behavior. The quality of steam pressure control can be measured by studying how well and how close to the set-point the steam header pressure stays. The steam pressure set-point during the recorded test runs was 10.7 MPa. Later on, after the test runs, it was possible to increase due to improved control performance up to 10.8 MPa.

The fuzzy logic controller seems to perform much better (see Fig. 54) than the conventional PID control during a longer period of operation. The number of data samples close to the set-point are remarkably larger when the FLC is used. As well, the typical behavior of the PID controller (to remain long periods below the set-point) is not shown in FLC histograms.

The top of the histograms are slightly below the set-point value (10.7 MPa) because the data was not recorded from the controlling loop but from a measurement loop which is located behind a valve in the steam header.

Although it is very important to keep the steam pressure at the set-point, the peaks up and down can be even more critical. According to the results recorded, a decrease to the deviation was managed as well as minimizing situations when the steam pressure is far from the set-point.

The most critical case, as mentioned before, is the sudden change from waste mix into sod peat as shown in Figs. 55 and 56. The PID seems to have continuous problems to stabilize the steam pressure. After the sod peat pulse at 05:30, the waste fuel flow decreases rapidly, but the pressure fluctuation seems to continue. The FLC can improve the control performance like the steam pressure performance after the sod peat pulse at 01:00 shows. The waste fuel-feed decreases even faster than in the case of PID but also seems to manage to prevent overshoot in steam pressure until the next sod peat pulse at 01:25 causes new disturbances. The fact that coal is not at all used in the case after FLC implementation has various influences to the steam pressure control. On the other hand, the usage of waste fuel makes the control simpler, but in practice the usage of coal helps the control of steam pressure when the sod peat is coming to the boiler. This can be explained: because of having coal fed to the boiler, the speed of the waste fuel line is lower and the resulting sod peat pulse is, naturally, smaller.

Altogether, the steam pressure performance controlled by FLC seems to be better with narrower fluctuation and the pressure stays closer to the set-point (10.7 MPa). The rather small load changes shown in Fig. 57 do not cause significant disturbances, while the major disturbances come from the fuel. It can be seen as well that the cyclone temperatures follow the steam flow because the higher the load the more fuel is needed. Higher steam pressure causes increased steam flow, which is one of the steam net's features (discussed in Chapter 5) and can also be found from Figs. 55, 56 and 57.

The conventional PID controller is realized as described in Chapter 4 (Fig. 21). The power need set-point to separate fuels is corrected by D-term from steam pressure change and from steam flow change. The maximum influence from the steam pressure change is ±3.6 MW, and from the steam flow change is ±9 MW, while the total range for the output is 0-180 MW.

The tuning parameters of the PID are adjustable depending on the bark/coal ratio and extra fuel information given by the operator. The extra information is a peat "flag", which the operator can set in order to change tuning. The gain K_P slides from 2 to 5 and K_I from 0.0028 to 0.0067 so that the biggest gain and shortest integration time is when the fuel contains a lot of peat.

The conventional PID steam pressure control has reached its present tuning during several years of operation. It was tuned with a strong gain in order to be able to handle large fuel quality and load changes. This situation often causes the PID controller to saturate; even though the steam pressure is below the set-point after a bigger steam pressure drops. Practically, it means that the gain, together with long integration time, prevents the rise of the steam pressure when it tries to reach the set-point. This effect can be seen from Figure 54.

By using fuzzy logic control, it was possible to diminish the problems described above. The best performance needs, however, a control structure where the PI-type fuzzy logic controller is supported by a strong derivative term. In the application, the influence of the derivative term to the set-point of the final power need is rather big (max -20 MW), non-symmetric and strongly non-linear. Particularly, these two properties (non-symmetric and strongly non-linear) seem to be the main strengths of the FLC implemented.

One reason for improved performance is the rather large, non-linear and non-symmetric values of the defuzzification parameters CNE (PI) and FNE (D) (see Fig. 41, Chapter 5) as well as the values of the CPE and FPE, which decrease and increase the power need set-point rather fast. In any case, the pressure rise can not be avoided because the controller can not react until the sod peat is already burning and producing steam. As well, the delays in control (min 2 s cycle time + 5 s data transfer) and delays in feeding lines generate the pressure pulse. Typically, one sod peat batch causes several pressure pulses both upwards and downwards caused by the fuel grading in silo and feeders.

The fuzzy logic controller was easy to implement and the basic tuning was done by using the operators’ existing knowledge of the process and its dynamics. The fine-tuning part correspondingly proved to be rather difficult and took several days. The complicity is caused by the large number of tunable parameters, and the fact that the tuning method used is typically trial and error. This, naturally, takes a lot of time and, in this case, the real combustion process was running all the time.

The need of the fine-tuning work depends totally on the type of FLC. The steam pressure controlled did not prove to be very robust. The lack of robustness appeared when the boiler had to run a two-week period exclusively without the steam accumulator connected to the steam net. During that period, the FLC performance was so bad that conventional control was used. The main problems were probably caused by the very big gain (see Fig. 44, Chapter 5) by K_P varying from 4.2 (min) to 16.4 (max) (cycle time 2 s) and by strong derivative term correction as well as by the difficult exceptional control task. In order to be able to cover that period with FLC, it would have to be re-tuned but because of the short period (two weeks) the new tuning work was not reasonable. The tuning parameters of the FLC and conventional PID were compared in Chapter 5.

So far, the tuning algorithms have not become very popular in industrial cases, and the tuning in this case was also done by using trial and error based on process knowledge. Tuning should not, however, be only just trial- and error-based. Therefore, it is relevant to recommend using tuning grips, which means that, for example, the gain of the FLC can be changed easily just by changing one parameter and the influence to all fuzzification or defuzzification parameters is similar. Finally, the most important thing in FLC tuning and implementation is to understand the process behavior properly so that the influence of fuzzification as well as the defuzzification parameters and the structure of the rule-base to the control output is correct in any operating environment.

6.4. Compensation of the fuel quality fluctuation

The basic idea behind the fuel heat value compensation is the combustion power control (Ryd 1994), which means continuous correction of the fuel-feed according to the combustion results (O_2) so that the combustion power remains as constant as possible (see Chapter 4).

When bio-fuels like bark, sludge or peat are used as the main fuel in a boiler, and the feeding system does not have any kind of fuel pre-mixing capabilities, the heat value fluctuation is one major disturbance in the combustion process and causes disturbances to the steam header pressure. The heat value changes are mainly caused by the dramatic changes in the moisture of the fuel. For example, in the Varenso K6 case, the waste fuel moisture varies from 25 % to more than 70 %. The ash content between different fuel types also varies greatly.

6.4.1. Karhula pilot plant

The fuel quality fluctuation compensation was one of the most tested applications in the Karhula pilot plant. The experiment results below were made by adding a small amount of dry bark to the fuel silo so that during the experiment, the feed quality varied due to partial mixing of the drier bark with the normal bark. At the beginning of the experiment, the fuzzy logic control of the compensation was not running and, after a while, it was activated. As one can see, the responses of bark feed screw speed and O_2 process value (shown in Fig. 58) compensation seems to stabilize the O_2 fluctuation quite well, if the tuning of the fuzzy controller is correct. During the experiment, the fuel-feed optimization was on but coal, as a support fuel, was not used.

After the gain of the fuzzy logic controller was increased, (as one can see from Fig. 58) the bark feed screw speed as well as the O_2 fluctuated significantly more than when the first set of parameters were used.

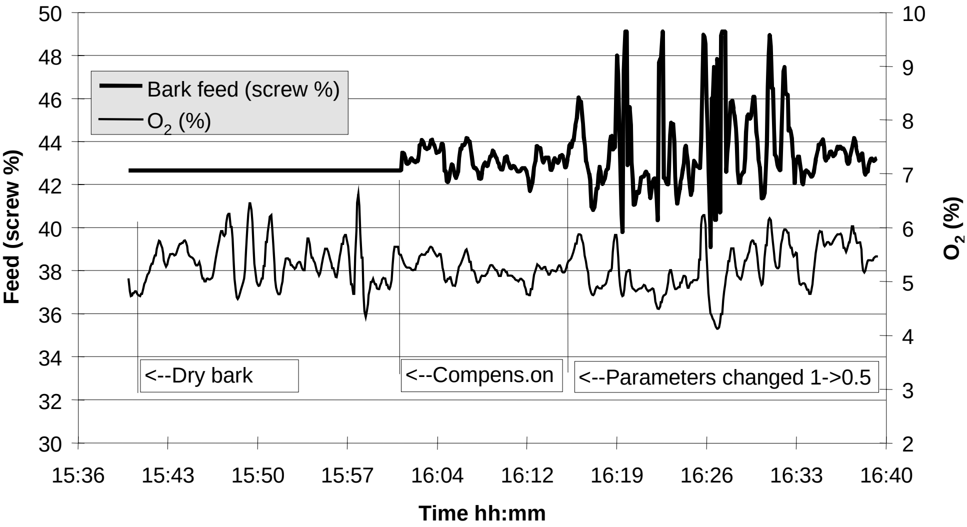


Fig. 58. Experiment results of the influence of the fuzzy compensation for the fuel quality fluctuation to the flue gas O_2 fluctuation.

The gain increase (factor change 1->0.5) means that all the fuzzification parameters (see Fig. 47, Chapter 5) are multiplied by 0.5. This gives very strong gain as one can see from the much bigger control actions of the fuel-feeding screw.

6.4.2. Varenso K6

As an indicator for the performance of the compensation of fuel quality, fluctuation was used with the O_2 histograms as well as the average and standard deviation of the CO process value of the flue gases. The fluctuations of the fuel quality are mainly caused by the changes in the moisture of the fuel. The ash content also varies between different fuels. The flue gas flow measurement could also be suitable to represent the fuel moisture, but that measurement was not available in the Varenso K6 boiler and it had to be ignored. Long-term results of the fuzzy compensation of the fuel quality fluctuation control are shown in Figures 59 and 60.

In Figure 59, the histograms of left and right process values of O_2 are shown. The data depicted are one week, three minute samples from Week 45 before, and Week 13 after FLC implementation. The reason why the histograms after the FLC implementation have “moved” closer to each other is the asymmetric bed correction control system, which is ignored in this thesis.

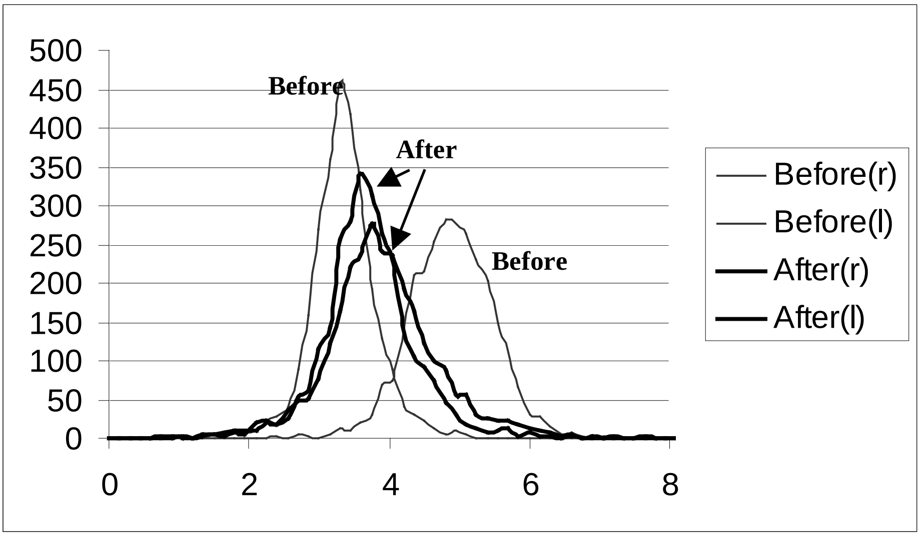


Fig. 59. Histograms representing the left and right O_2 process values of the Varenso K6 before and after the FCL implementations.

In Figure 60, standard deviation of O_2 from Weeks 49 (before FLC) and from Week 12 (after FLC) are compared. The two other bars indicate the usage of sod peat during those weeks. In Week 49, 28 trucks were clocked in to the power plant, and in Week 12, 39 trucks respectively. The standard deviation is calculated from the average of left and right O_2 measurement. The O_2 set-point is constant and does not vary based on fuels, but was changed from 3.2% (Weeks 45-49) to 3.6% (Weeks 12-13) for winter months when most of the sod peat was used. This change was not due to the experiments but a normal change in operating routine because of different load levels.

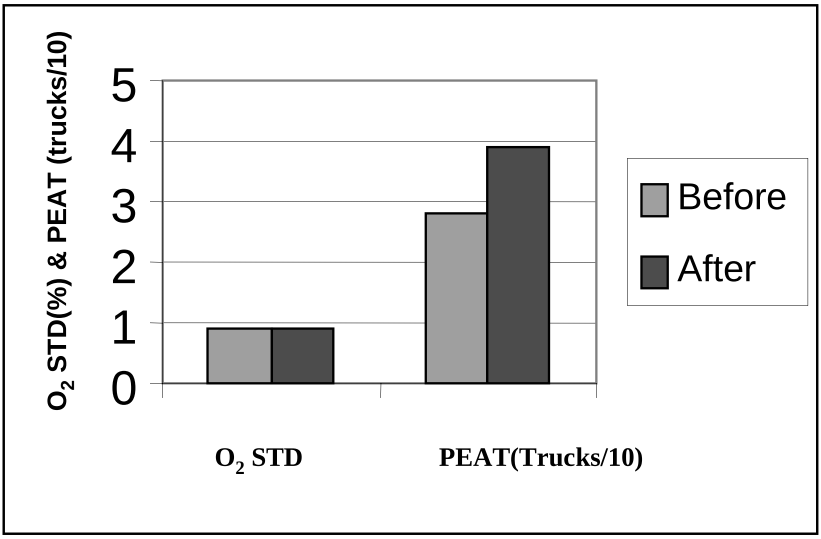


Fig. 60. The standard deviation of the flue gas O_2 before and after FLC implementations compared to a weekly used peat (number of peat trucks/10).

The flue gas CO indicates the combustion circumstances inside the combustion chamber. The risk of the increase of CO in the Varenso K6 boiler is always real when the sod peat or some other high quality fuel-feed is started. This is, naturally, caused by the higher combustion air consumption of the dry sod peat per mass flow unit. Because the combustion air is controlled according to the fuel mass flow, the combustion air control is not able to handle the fast change in the air demand. The fuzzy heat value fluctuation compensation together with the steam pressure control, however, reduced CO emissions. The average and standard deviation of CO during one week before and after is depicted in Figure 61.

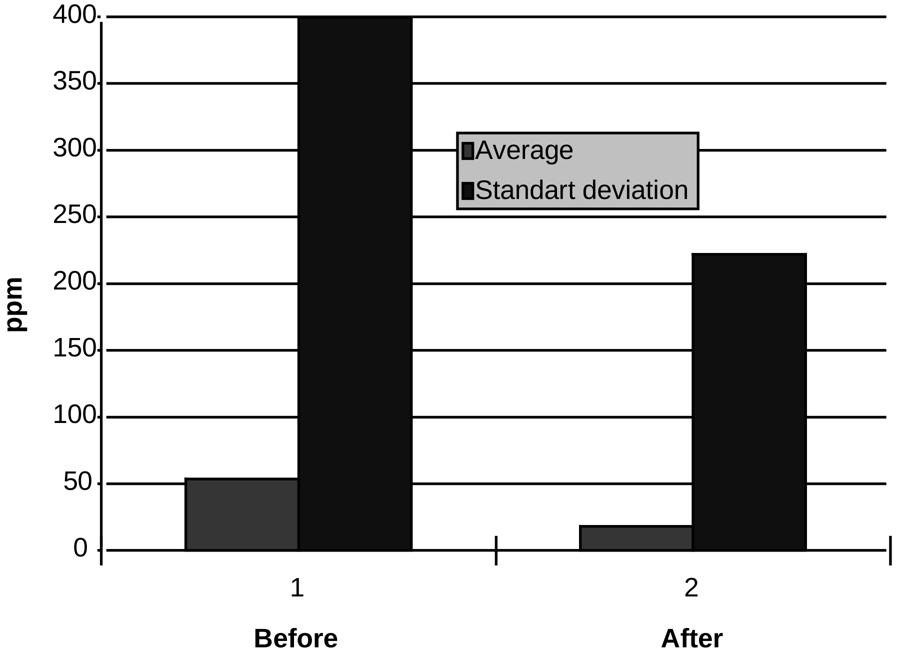


Fig. 61. Average and standard deviation of flue gas CO before and after FLC implementation.

According to the three minute average sampler during a one-week period, the CO average decreased by 68 % and standard deviation by 44 %. As mentioned above, the CO emissions are highly dependent on the sod peat usage. During the weeks where the results above were collected, the peat usage was about the same (1016 t before the FLC implementation in Week 48, and 1127 t after the FLC implementation in Week 13).

6.4.3. Discussion

The fuzzy compensation for the fuel quality fluctuation in the Karhula pilot plant experiments seemed to work properly, but it was assumed that it still needs much tuning in order to reach complete compensation. The fuel quality fluctuations were demonstrated by using dry bark or cutter chips and oil, but cutter chips did not pass through the feeding screw as expected and those experiments were not successful. However, many steps in fuel-feed quality were completed and the compensation always made correcting actions in order to keep the O_2 level as constant as possible. As shown in Fig. 58, with reasonable tuning, the flue gas oxygen variation decreases significantly, while the fuel-feed screw speed is continuously changing. In pilot plant results, the influence of the other controllers was insignificant because the fuzzy steam pressure control was not in use and the O_2 trim was tuned to be slow.

In the Varenso K6 industrial boiler, the most dramatic fuel quality changes take place when a truck of dry sod peat unloads into the feeding silos and the dry peat is introduced to the combustion chamber using the same waste fuel-feeding line as wet low grade waste fuel. During a very short time period, the fuel heat value increases by the factor of two or three and the increased combustion power can be seen very easily from the steam pressure and also from temperatures measured at the top of the combustion chamber and cyclones. Simultaneously, the combustion air fed according to fuel mass is not sufficient to oxygen consumption and the flue gas O_2 decreases very much.

The lack of O_2 is due to mass flow-based air feed calculation and dry sod peat is very light but has very high heat value. In the worst case scenario, the sod peat does not burn in the combustion chamber, but forms CO which does not burn until an oxygen-rich atmosphere is available in the cyclones. Another factor for not burning lower in the combustion chamber is inadequate mixing of the light particles of the dry peat.

As one can see from the results, the O_2 variation after FLC implementation did not decrease from the previous one in the Varenso K6 boiler (see Fig. 59). During both test weeks (before and after FLC implementation as seen in Fig. 60) the standard deviation of the O_2 was about 0.9. Similar types of results can be seen from Figs. 55 and 56 as well. In any case, there is reason to believe that the FLC improved the control performance because the sod peat consumption during the week after FLC implementation was much larger (39 trucks) than during the reference period (28 trucks). As discussed previously in Chapters 4 and 5, the sod peat, when introduced to the combustion chamber, causes the most disturbances to combustion.

For the steam pressure control, the successful compensation of the fuel quality fluctuation is very important. It means that the fuel disturbances can be at least partly damped and the steam pressure controller can more easily manage the steam pressure changes. The most important task of the compensation is not to try keep the O_2 at the set-point, but to help the steam pressure control. This is evident because the compensation controller is faster and the fuel quality fluctuation, when compensated, does not affect the steam pressure as much.

The flue gas O_2 variation in a multi-fuel CFB boiler seems to be continuous around the set-point, and according to the author’s experience, this kind of small variation should not even be tried to be leveled out. When the deviation increases more than 1 % of O_2 in the flue gas, the control actions are needed because it is a clear message of changes in fuel properties and combustion performance.

During the tests run discussed above, the Varenso K6 boiler operated normally with all existing control actions including fuzzy steam pressure controller and the O_2 trim. The process response using only fuel quality fluctuation compensation alone was not possible to record because of the continuously running process and the structure of the control procedures designed. The O_2 trim is realized with two controllers based on the left or right of O_2 and are tuned to be rather slow with K_P (0.7 if right or 0,5 if left), K_I (0.0042 if right and 0.0021 if left) and K_D (0). The active controller is selected based on the minimum O_2 measurement. The controller based on left oxygen measurement is tuned to be faster. The obvious reason is that typically the O_2 measurement left is lower (see Fig. 59). It means that the left side of the combustion chamber obtained more fuel because of the structure of the feed lines (see Fig. 6, Chapter 2). The O_2 trim controls the oxygen content by secondary air.

However, an effort must be made to keep compensation of the fuel quality fluctuation as a pure disturbance controller so that it reacts fast enough to fuel quality changes, but lets the O_2 trim take care of the oxygen content control with slower behavior.

The greatest benefit of using fuzzy application in fuel quality compensation control can be found from the non-linear nature of the controller. The non-linearity was done by fuzzification parameters (see Fig. 46, Chapter 5). Particularly, the fuzzification of error proved to perform better when non-linear.

The maximum correction allowed for the waste fuel heat value was ± 15 %. In practice, the heat value changes are much bigger and it would be interesting to test even bigger compensation as ± 15 %. In running an industrial boiler, the risks are too large for those types of experiments.

The original purpose was to calculate the waste fuel heat value before the compensation, but practice showed that the calculation in that kind of environment (like Varenso K6) was impossible to do reliably. The calculated heat value was fluctuating so much that it was not possible to use for control purposes. The main reasons for that were inaccurate measurements of the fuel mass flow, combustion air flow and steam flow. For these reasons, it was decided to use fixed average waste fuel heat value, which was corrected as described above.

In view of further research, it would be interesting to model the existing process delays from fuel-feed measurement into the flue gas O_2 measurement as well as the staging of the combustion air as a component of the compensation structure. Naturally, the best arrangement would be the possibility to use reliable, online moisture measurement for estimating the heat value of the fuel mix containing several types of fuel components.

6.5. Fuel-feed optimization

6.5.1. Karhula pilot plant

In the Karhula pilot plant, one fuel-feed optimization experiment was made. In the experiment, as depicted in Fig. 62, the coal feed decreased to zero, and bark replaced the missing coal portion, when the optimizing procedure was activated (Auto). Optimization was tested by setting the fuel prices in objective function so that coal was 10 times more expensive than bark. The bark flow does not replace the coal immediately after the optimizing start because the system contains ramping functions in order to make the changes smoother to the process.

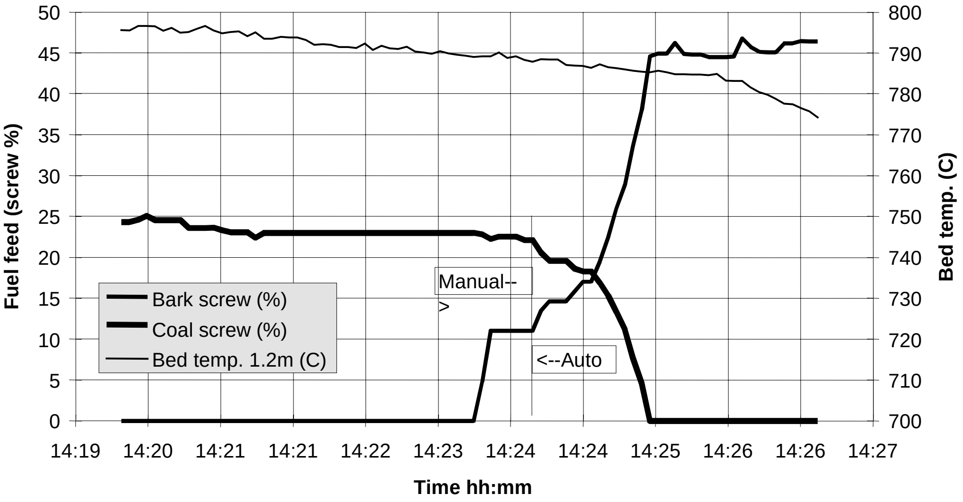


Fig. 62. Fuel-feed optimization experiment results made in Karhula pilot plant.

One experiment was sufficient due to expected results and lack of experiment time. This experiment was made just to test the correct implementation of the planned application. The system worked as expected and only the constraints in optimization equations proved to be complicated and had to be reprogrammed before the industrial boiler installation.

6.5.2. Varenso K6

The main task of the fuel-feed optimization in Varenso K6 is to minimize the coal usage. Coal is a much more expensive fuel than the waste fuel mix used but is needed as a support fuel during bigger load and disturbances.

In Figure 63, coal usage (coal x10 / waste fuel) is compared using a nine-month time period from 1997 and 1998. The time period (March-December) was used because the optimization procedure had been running since March 1998.

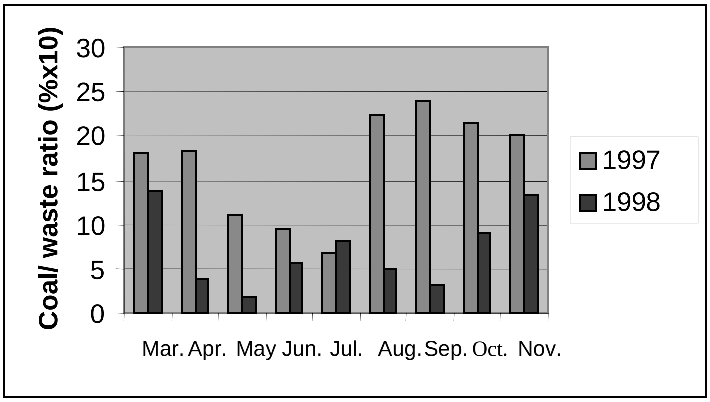


Fig. 63. The monthly average of percentage [100x kg/kg] (multiplied by 10) of coal from the waste fuel-feed to the Varenso K6 boiler. The data compared is calculated from daily averages 1.3.1997- 6.12.1997 and 1.3.1998-6.12.1998.

The total amount of coal used during the nine-month periods were 9147 tons (1997) and 3607 tons (1998), which means that during the same time period in 1998, 5540 tons less coal was used.

6.5.3. Discussion

As previously mentioned, in Varenso K6’s case, the fuel-feed optimization in practice is continuous minimization of the coal feed. Coal is far more expensive than other fuels used like bark and wastes. However, coal is required as a support fuel when the load is so high that steam demand can not be fulfilled by only using waste fuel lines alone. All the problem situations like fuel silo bridging and fuel trips have to also be compensated by coal.

As one can see from Fig. 63, the reduction in coal consumption is dramatic. These results must be discussed within tight criterion because there are many parameters which influence the coal usage. Such are previously mentioned disturbances like fuel silo bridging and fuel trip. Boiler start-ups and high boiler load, the capacity of the flue gas fan and bed temperature control also increase the usage of coal. Naturally, the load limit when coal is needed as a support fuel depends, of course, on the quality of the used waste fuel mix.

Although the coal consumption relies on so many different factors, there is reason to believe that replacing manual, human decision-based control by automatic control, significant savings can be achieved. This is shown extremely well during the summer and autumn period, when the load level is naturally lower. During this period it was possible to save coal because it was not fed to the boiler just for making the base load. The main difference from the previous manual control is the fact that the systems use coal only when it is really needed. Previously, the coal usage relied on the operators and their habits to start coal feed in different situations.

A good example of coal usage can be found from Figs. 55 and 56. When the operators could decide the usage of coal, it was used rather often compared to the corresponding time period when the optimization procedure was running (see Fig. 56). Operators typically used coal for steam pressure stabilization, but the results depend on the experience of the operator and the performance was not always very good as one can see from Figure 55.

The reason why operators favored coal is that when using it as a support fuel, the combustion performance is better and less problems and alarms appear. This means that by minimizing coal consumption, the boiler’s availability and steam pressure control performance should become worse. According to the results recorded since FLC and optimization implementation, this was not the case. Thus, as a result, it can be stated that the decreasing of coal feed did not worsen the availability and performance of the steam pressure because of the improving influence of the implemented FLC controllers.

One extra problem in coal minimization in the Varenso K6 boiler is the fact that the coal feeders, when started, always produce step-wise a minimum coal flow of at least 0.6 kg/s. If this minimum feed could be decreased, the total savings of the coal would be even greater.

In the Varenso K6 case, the optimization was done on just the cost basis and between coal and waste fuel mix. The composition of waste fuel is impossible to effect because the mixing simply takes place manually without any control possibilities. Manual mixing means the occasionally unloading trucks, which are transporting all the other fuels (sludge, saw dust, sod peat, cutter chips, etc.), which have been loaded batch-wise into the waste fuel silos, together with bark.

If more than two fuel-feed lines are available, all of them can be included in the optimization procedure. Other bases than energy prices should also be interesting to test, and this kind of optimization objective could be emissions or limestone usage.

6.6. Increased fuel inventory monitoring

6.6.1. Karhula pilot plant

An example of the experiment made for the fuzzy logic decision-making application is introduced in Fig. 64. The experiment was made by making steps in coal feed by changing coal feeding screw speed from 30 % to 60 % for a few minutes, which means a dramatic increase of the coal and will, in any case, cause an increase in the char in the bed. Responses depicted are the fuzzy sensor Char In Bed (CIB).

The fuzzy sensor CIB is a result of fuzzy logic decision-making (see Chapter 5) and it indicates that the amount of the char (unburned carbon) in the bed has increased.

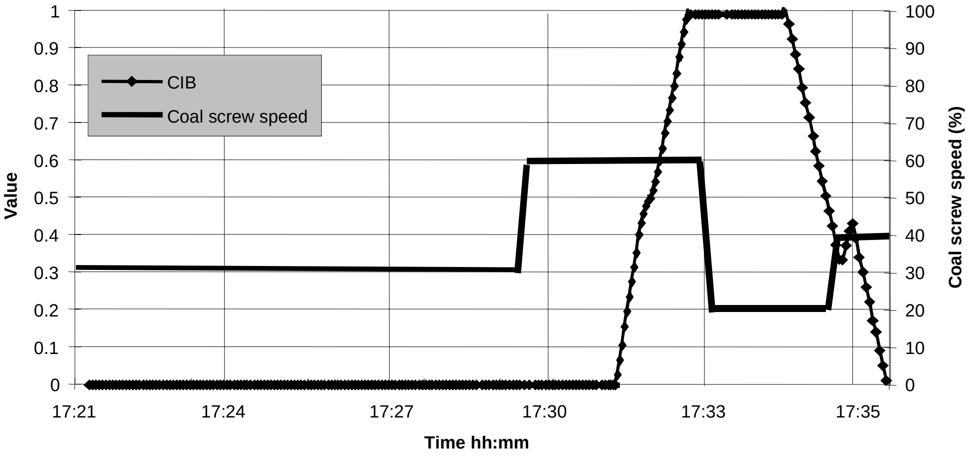


Fig. 64. The fuzzy sensor CIB and sintering threat indication with coal feed step in increased fuel inventory experiment at Karhula pilot plant.

In Figure 65, the bed temperature and the flue gas O_2 from the same experiment are shown. The flue gas O_2 decreases from 6.5 % to 3.5 % after the coal step while the bed temperature shows only a small increase.

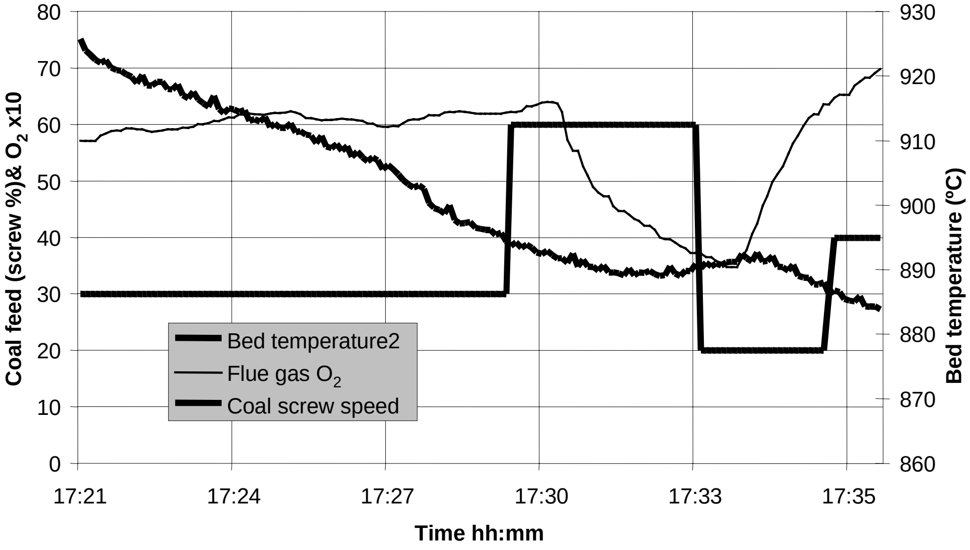


Fig. 65. The coal feed screw speed, flue gas O_2 (x10) and bed temperature in fuel inventory experiment at Karhula pilot plant.

6.6.2. Varenso K6

In the Varenso K6 boiler, it was not possible to make any experiments by coal feed steps because it has so critical a role in mill steam production. This is why no valuable recorded data was available. However, the performance of increased fuel inventory indication was followed occasionally during the test runs and the performance is briefly discussed below.

6.6.3. Discussion

The fuzzy decision-making logic was used in the form of fuzzy expert system for fuel inventory monitoring. The experiment results depicted in Figs. 64 and 65 shows that the fuzzy sensor CIB indicates a char increasing in the bed after a significant coal feed step. The step was so big that the technicians and pilot plant operators did not dare to keep the coal feed so high any longer. Actually, the only evidence for the increasing bed fuel inventory was the operators' experience from the pilot plant's operation because no samples from the bed or other analysis were impossible to make. From Figure 65, it can be seen that the flue gas O_2 decreased during the coal step. The O_2 was rather high continuously because of security reasons. Therefore, the applications seemed to work and the experiments in the Karhula pilot plant were encouraging.

The fuzzy logic enables decision-making by using large amounts of inputs from the process, and, as a result, one can get the fuzzy software sensor which indicates the process status and development with one figure scaled, for example, from 0 to 1 or from 0 to 100. By forming this kind of sensor, a group of process values has been processed to a more exact and easier understandable form and can be further used for process control actions, or alarming through fuzzy logic controllers, or directly.

The tuning of the fuzzy logic decision-making systems was easier than the fuzzy logic controllers. In the cases discussed in this thesis, a large amount of process value fuzzifications were tuned using operators' and engineers' process knowledge and setting rough parameters. The fuzzification to three membership functions was also sufficient in most of the cases.

For the operators, the fuzzy sensors can provide more pre-processed information on the process status and development than conventional single process value measurements. For example, instead of following ten different process values, the operator just needs to follow one fuzzy software sensor, which has been constructed by following a similar kind of decision structure as an operator makes him- or herself. These fuzzy sensors or terms can be used in process control in many ways. They are suitable for input to fuzzy logic controllers or alarming systems or for operator information only. Another question is how easily does the operator become familiar with fuzzy sensors if they have been accustomed to follow certain meters and indicators.

As mentioned before, in the Varenso K6 boiler it was not permitted to make any kind of test to decision-making logic. However, tuning was done with the power plant operators so that it should indicate if the increased bed inventory would appear. The indicators of decreasing and increasing char were followed occasionally and they showed correct performance in normal operation. Anyhow, it proved to be very difficult to test such applications in a boiler which is in operation continuously and when no tests are allowed.

In a multi-fuel industrial boiler like Varenso K6, the too much-increased fuel inventory must be handled as an abnormal and undesired situation, though some fuel inventory always appears when the boiler operates. Significantly increased fuel inventory can only be caused by too big coal feed related to other burning conditions, which typically takes place only with serious waste fuel-feed difficulties. In theory, big fuel particles like sod peat could also cause fuel inventory, but in practice it is hardly possible except when the moisture of the sod peat is high.

According to the author’s experience in a multi-fuel CFB boiler, the fuel inventory can not be used for control purposes. The main reason is that a boiler like Varenso K6 is operating by waste fuel and coal, which generates the increased fuel inventory and is just a support fuel and occasionally in usage.

In the decision-making logic, the process values and changes of the process values from fuel-feed, bed temperature, bed pressure, steam generation, flue gas O_2 and CO were used as inputs. Additionally, the variance of bed temperatures including the variance of bed temperature change and the variance of bed pressure could be worth testing. These are very suitable indicators when the presumable sintering threat is desired to be forecast. Naturally, the quality of the information available through these variables depends on the amount and quality of measurements installed to different sections of the combustion chamber.

7. Conclusion

The goal of this research work for this thesis was to find new solutions for multi-fuel Circulating Fluidized Bed (CFB) boiler control challenges. In the first phase, the main work was to define the problems and the process behavior behind the problems which operators faced in their daily routines. In the second phase, the suitability of using advanced control methods to solve these problems were studied. The solutions were based on an idea of process behavior, and the implemented methods were fuzzy logic control and fuzzy expert system. The planned application solutions were tested in a CFB pilot plant in order to reach better understanding of the suitability of control methods and the CFB combustion process behavior. The experiments gave a lot of information and helped this work with the industrial boiler implementation. Finally, the solutions based on fuzzy logic and other advanced control structures were implemented in a fullscale industrial multi-fuel CFB boiler.

Because the basis for this thesis was a research and development project with three companies and continued as a commercial control system implementation project, the amount of developed applications was large. Therefore, due to the commercial research and development project, it was not possible to introduce the structure and properties of the applications in a very detailed way. Instead, some examples of the main applications and discussions on how fuzzy logic and fuzzy control were implemented in different cases were introduced.

As a hypothesis, it was stated that the fuzzy logic in control and expert systems is a notable tool for a control engineer to improve a CFB boiler control.

Fuzzy Logic Control (FLC) was shown to be suitable for implementing non-linear control cases in an industrial fullscale CFB boiler. Implemented applications gave better control performance than PID when non-symmetric control like steam (header) pressure is needed. Based on the author’s experience, FLC is worth testing in the kinds of cases where conventional control structure does not fulfill the needs. Best performance was shown by an FLC including derivative functions with strong influence to the control output.

FLC was shown to be able to dampen disturbances caused by fluctuation of the bio-fuel mix heat value. This was shown especially well during the experiments in the Karhula pilot plant, where the other (disturbing) controls were possible to mask out. In the Varenso

K6 boiler, the improving influence was more difficult to show even with successful operation.

Fuel-feed optimization procedure with dynamic constraints worked successfully and has decreased the usage of coal, which is the most expensive fuel in the Varenso K6 power plant, dramatically. Simultaneously, it has not risked the boiler's availability, though the minimization of coal usage could cause it to do so.

Expert systems for increased fuel inventory monitoring shown in pilot plant tests gave good performance, but it was extremely difficult to test satisfactorily in the industrial boiler environment.

The steam pressure control introduced can be used in any boilers where steam pressure and steam flow measurements are available. Fuel quality fluctuation compensation is very reasonable to try in multi-fuel cases but does not need any other measurements than flue gas oxygen. If the waste fuel heat value is to be calculated, the boiler energy balance calculation needs a great deal of measurements. The calculated waste fuel heat value can satisfactorily be replaced by fixed average heat value as done throughout this research work. In any case, the fuel quality changes can not, in industrial practice, be noticed earlier from the process than from combustion results. In order to compensate the fuel quality changes totally, one should be able to measure the fuel heat value or at least the fuel moisture online.

The fuel-feed optimization can be used if more than one independent fuel-feed line is available and the fuels have significantly different prices. As an objective function, it could also be interesting to test emission-based optimization problems instead of energy cost-based optimization.

The expert system for the increased fuel inventory monitoring needs several measurements from the boiler and gives more reliable indications the more that measurements are available. The fine-tuning of that kind of application in an industrial environment can be difficult because sufficient experiments can be challenging to carry out.

The FLCs and the fuzzy expert systems should be maintained as simple as possible since the tuning work with complicated fuzzy structures is rather difficult due to the large number of tunable parameters. Without proper process knowledge, the implementation of FLCs is very difficult. In the author's experience, interviewing the operators and mill engineers is sufficient to implement an FLC, but the control engineer must know the process behavior. The better the understanding of the process, the better control designs can be reached irrespective of the control method used.

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APPENDIX 1

Results of the Varenso K6 test runs

APPENDIX 1 introduces the results of test runs made in Varenso K6 boiler. Weeks 45, 48 and 49 (1997) represent the period before implementation of the new FLC applications, introduced in this thesis, and Weeks 12 and 13 (1998) the period after FLC implementations. Week 45 differs from other weeks in flue gas O_2 distribution in the combustion chamber because the bed symmetry control (not introduced in this thesis) was already implemented in Week 47.

Figure A1 shows the steam pressure histograms, Fig. A2 the average and standard deviation of the steam pressure, and Fig. A3 the improvement of the steam pressure FLC during the tuning period. Figure A4 shows the averages and standard deviations of the flue gas CO and Figs. A5-A6 the same for left and right flue gas O_2 process values. Figure A7 shows the number of sod peat trucks clocked in the boiler during the test run weeks.

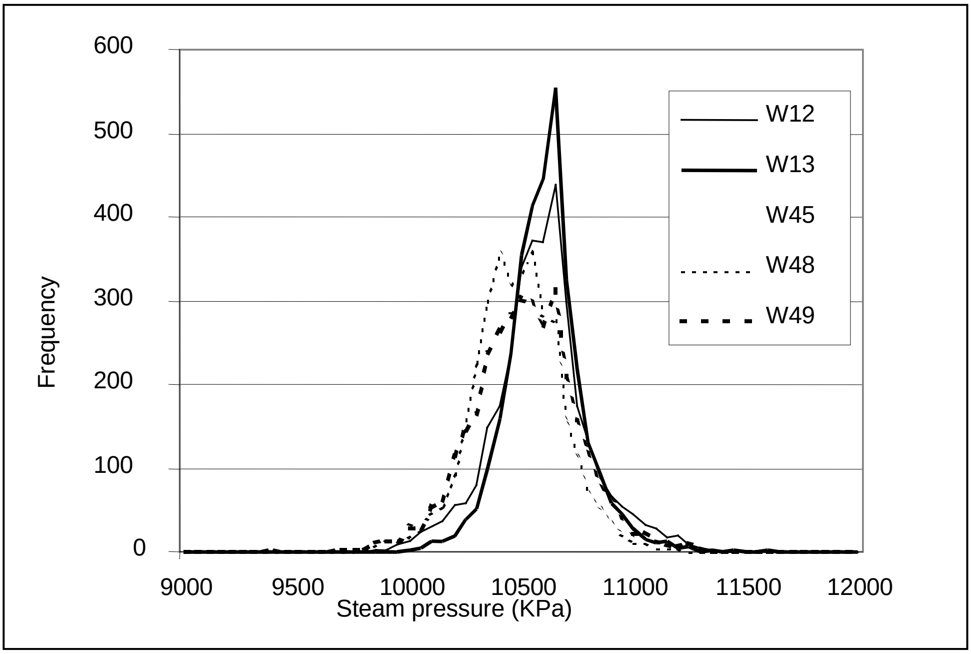

Fig. A1. Steam pressure histograms recorded from Varenso K6 boiler. Week 45 data is not drawn due to lack of possibility to record said data period.

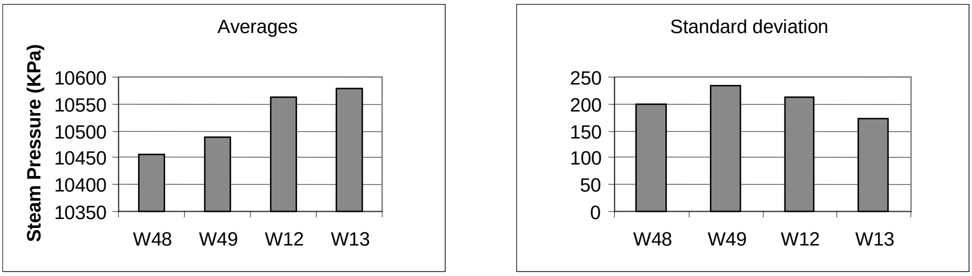

Fig. A2. Averages and standard deviations for steam pressure recorded from Varenso K6 boiler in Weeks 48 and 49 before FLC implementations and in Weeks 12 and 13 after FLC implementation.

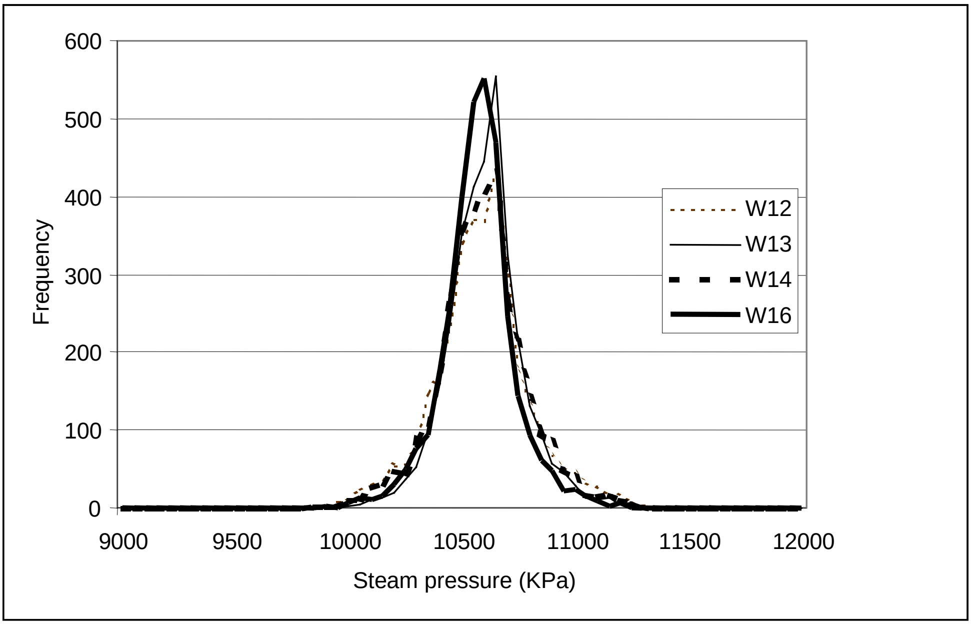

Fig. A3. The improvement of the steam pressure control during the tuning period of the FLC controller in Varenso K6 boiler.

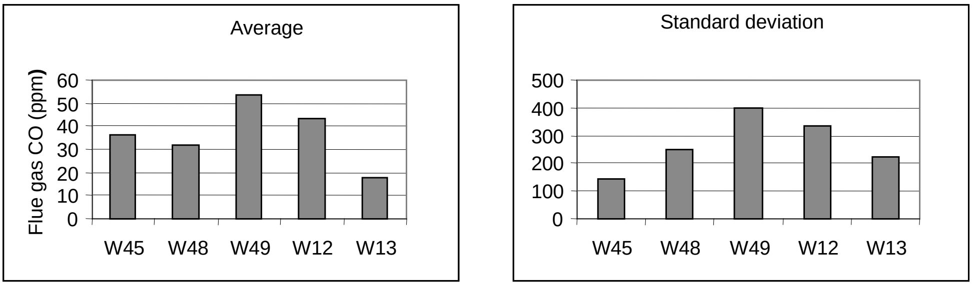

Fig. A4. Averages and standard deviations of the flue gas CO recorded from Varenso K6 boiler.

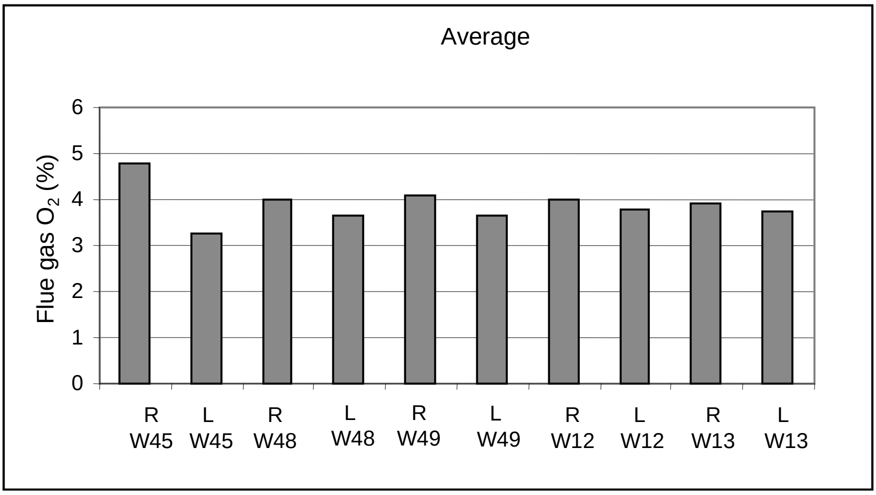

Fig. A5. Averages of the right and left flue gas O_2 process values recorded from Varenso K6 boiler.

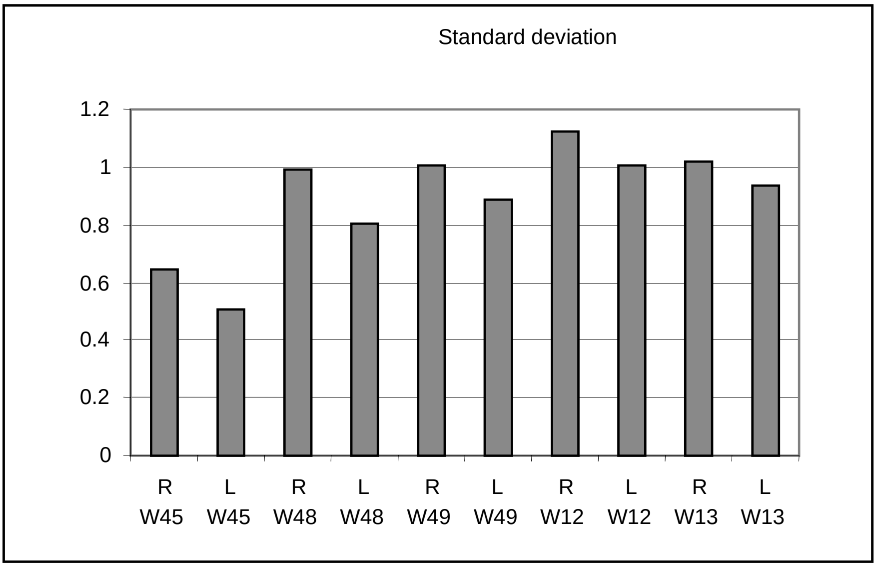

Fig. A6. Standard deviations of the right and left flue gas O_2 measurements recorded from Varenso K6 boiler.

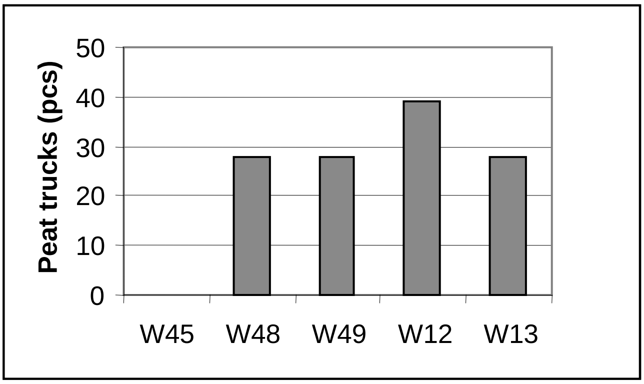

Fig. A7. The number of peat trucks clocked in to the boiler during the test run weeks.