DEVELOPMENT OF ACC CONTROLLER WITH MATLAB/SIMULINK

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Introduction

The objective of the Advanced Combustion Control (ACC) project was to develop a prototype of the next-generation boiler controller providing optimal efficiency while minimizing emissions for pulverized-coal fired boilers operating in cycling regimes. The solution developed by the Honeywell Technology Center Europe in Prague is targeted to the Central and Eastern Europe area with a considerable share of pulverized-coal boilers.

The solution was implemented as a part of the Honeywell TPS (Total Plant Solution) distributed control system on APP (Application Processing Platform) node, which is a Windows NT based environment for advanced control applications. The communication with the DCS (Distributed Control System) is via the OPC (OLE for Process Control) client/server technology. Using the open OPC interface, the optimizer can be applied over baseline DCS of other producers as well. The solution is currently running at the heat plant TOT Otrokovice on pulverized-coal fired boiler K5 (125 tons/h of steam, 9.3 MPa, 540 °C) and will be extended to the remaining boilers K3 and K4 in the near future.

To verify the feasibility of the novel model-based predictive control and cautious optimization strategies, prototype solution was developed using MATLAB and Simulink. Also, for the development of boiler models necessary to tune the model-based predictive controller, additional MATLAB/Simulink tools for well defined, repeatable experiments and their evaluation were developed. To enable real-time communication with the Honeywell distributed control system TPS, the functionality of the RT toolbox was extended – in cooperation with Humusoft Prague - by a TCP/IP driver and RT HCI/OPC server.

ACC Solution

For low NO_x burning with considerably reduced excess air, tight coordination of the fuel and air supply is necessary. The solution is based on a non-linear predictive controller with ROC functionality (Rate Optimal Control) and tightly coordinates the fuel and primary, secondary and tertiary air flows (see Figure 1) while taking into account different dynamics and rate limits.

The Prague branch office of Honeywell Technology Center Europe, in cooperation with District Heating Plant Otrokovice has developed a suite of three applications, for delivering optimal thermal efficiency while minimizing CO and NO_x emissions for pulverized-coal fired boilers operating in cycling regimes.

The modules are as follows:

- **Standardized Conventional Boiler Controller (SCBC)**
- **Combustion Controller**
- **Combustion Optimizer**

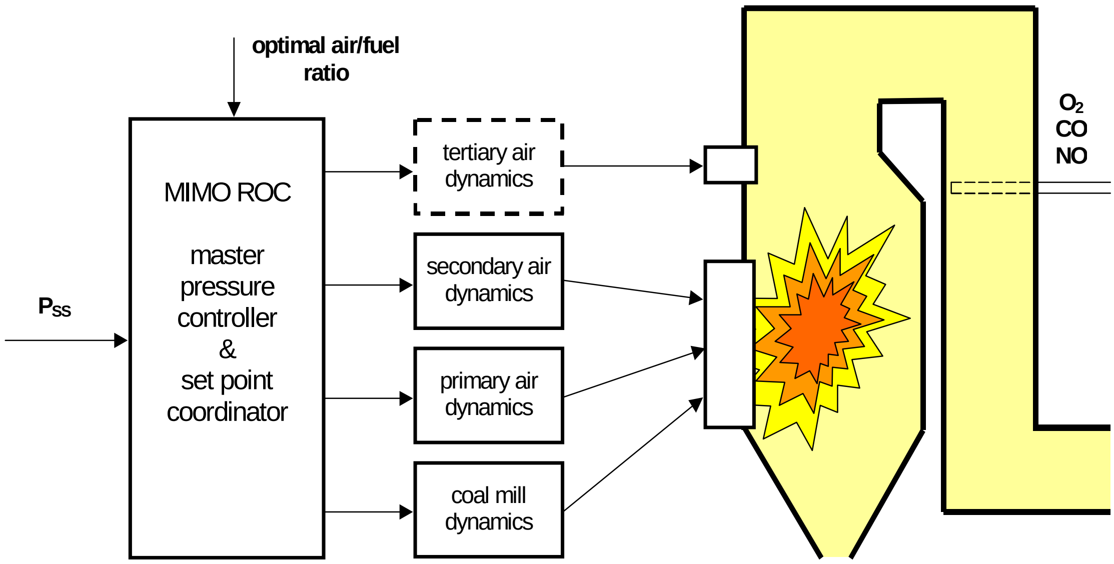

Figure 1. Combustion Controller Structure

The **Standardized Conventional Boiler Controller** application is an expertly designed conventional control system for boilers that runs in Honeywell High-performance Process Manager (HPM) controller. The software module can be used separately as well as a prerequisite for the application of advanced controls. The module has a general structure developed in cooperation with the Czech experts in boiler regulation. (EGÚ). It implements the best practices approach to boiler controls instrumented with all necessary tie-ins to the advanced controls layer. Special attention was paid to the separation of "local" and "global reconfiguration" logic control to obtain a scalable solution in which the difficult-to-control loops (e.g. those with a high degree of interaction among manipulated variables, complex dynamics and delay, or strong impact of measurable disturbances) can easily be replaced by the MIMO ROC Controller application or other advanced controllers.

The **MIMO ROC Combustion Controller** application is a model-based predictive multivariable rate-optimal controller capable of accurately maintaining the desired air-to-fuel ratios in the presence of disturbances and under equipment and safe operation constraints. It runs on the TPS APP node connected to the plant's DCS using the OPC (OLE for Process Control) communication standard. For low NO_x burning, tight coordination of the fuel and air supplies is essential. While easy to accomplish at steady states, maintaining the desired air-to-fuel ratios becomes a challenge for transients, when the controller has to match the coal transport and pulverized dynamics with those of the air supply paths, all under rate constraints imposed by the boiler hardware. The new MIMO ROC solution is equipped with sophisticated data pre-filtering and disturbance estimation features tailored to applications in power and heat generation. It allows precise control of the air-to-fuel flow ratios and other selected process variables under various process constraints. Its new computational engine uses model-based predictive control technology (MPC) with range control features (see Figure 2).

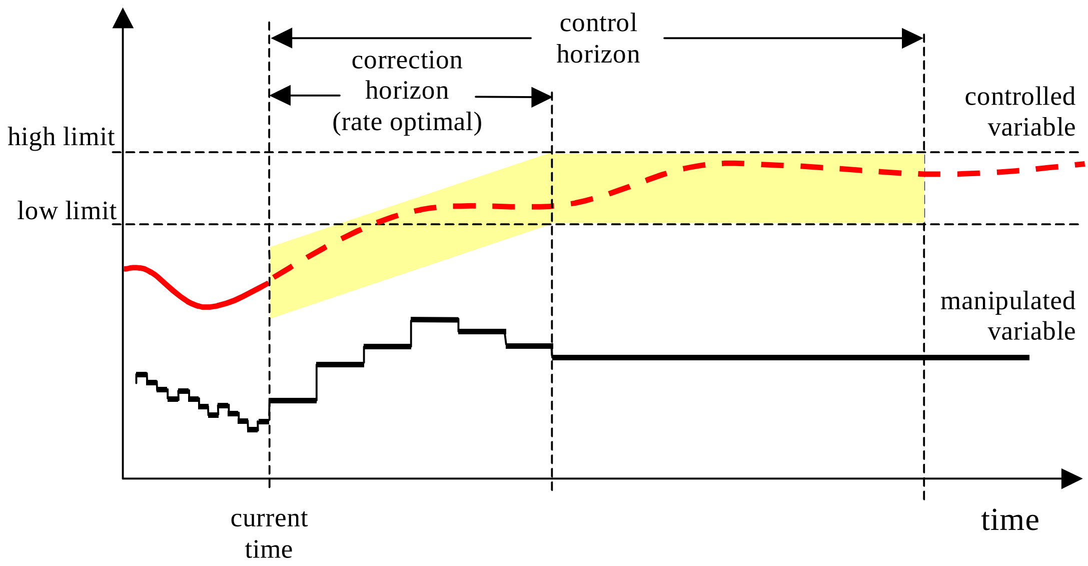

Figure 2. MPC performance specification

For a typical application as a master pressure controller with simultaneous air/fuel ratio coordination, the configuration of the models used in the MIMO ROC Combustion Controller is depicted in Fig. 3.

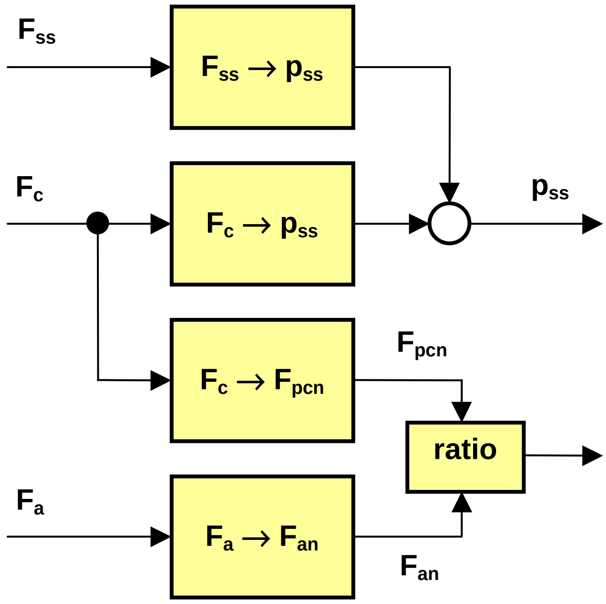

Figure 3. Combustion controller - model configuration

The Combustion Optimizer application provides the optimal air-to-fuel ratio and optimal O_2 level set points for the combustion controller as they vary depending on the current operating conditions and user preferences on heat efficiency vs. emissions production. It also runs on the TPS APP node.

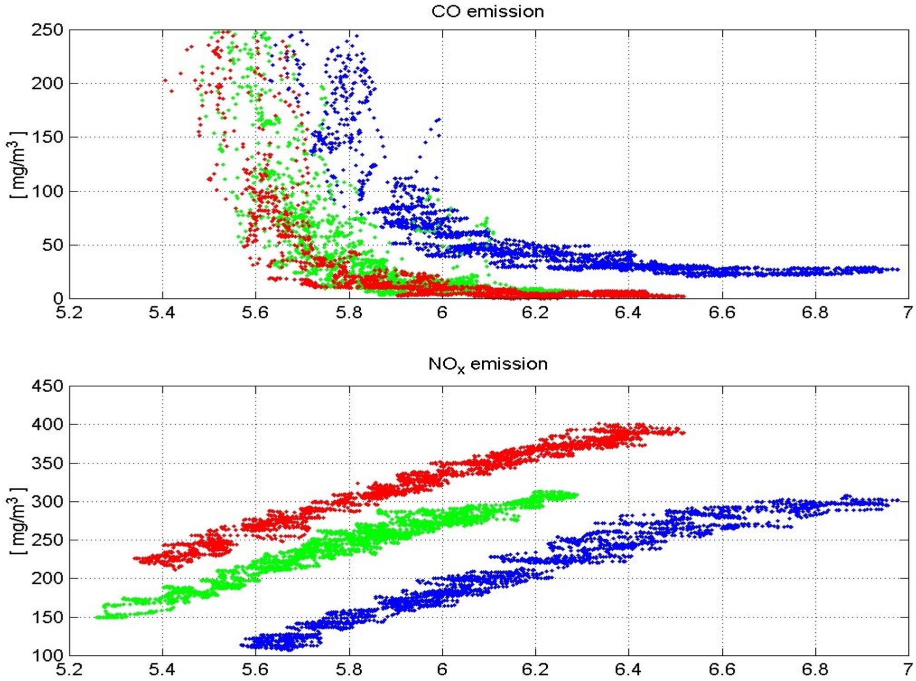

Figure 4. Typical emissions concentration data (load 120/90/60 T/hr)

As a plot of typical data from the flue gas analyzers shown in Figure 4 suggests, the variability of the CO production rate as a function of air-to-fuel ratio (m^3/kg) increases greatly with decreases in excess air. Yet, low excess air is desirable for both low NO_x burning and high efficiency. A *cautious* optimization strategy employed by the Combustion Optimizer takes into account not only the average CO and NO_x production rates at a given power level, but also the uncertainty (variability) of the prediction. The error bars in Figure 5 determine the feasible range of air-to-fuel ratios, over which the optimization is statistically guaranteed not to exceed the CO and NO_x emissions limits while maximizing the thermal efficiency of combustion.

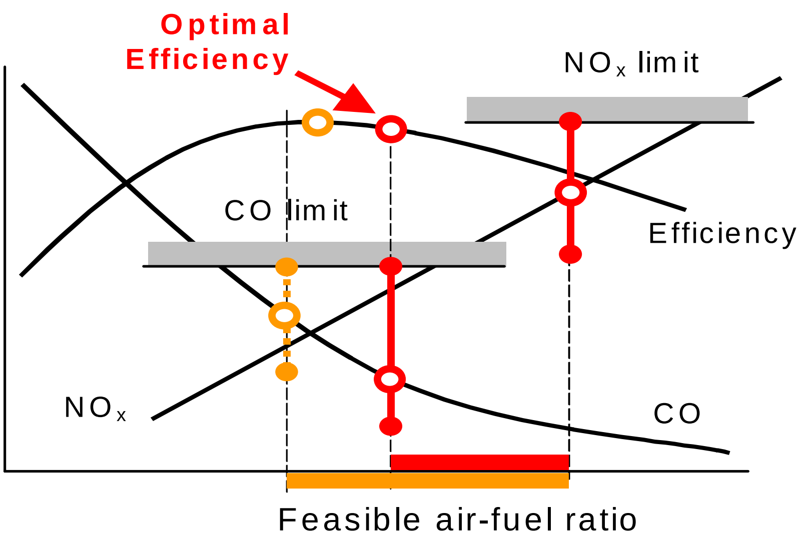

Figure 5. Cautious combustion optimization strategy

Open OPC-based Implementation

The Combustion Controller and Combustion Optimizer are implemented as two independent software applications to be run on a TPS APP node, which is a PC-based platform with the Windows NT 4.0 environment. The communication between the APP node and the remaining parts of the TPS distributed control system is based on the latest OPC client-server technology, implemented as a Honeywell TPN server.

OPC, which stands for "OLE for Process Control," is a new communication standard developed by the OPC Foundation (worldwide consortium of ABB, Fischer-Rosemount, Honeywell, Rockwell, Siemens, Toshiba, Yokogawa, and about 40 other major control companies). It is based on the Microsoft Windows NT and OLE (Object Linking and Embedding) and DCOM (Distributed Component Object Model) standards. The primary goal of the OPC is to open the proprietary environments of control systems of particular manufacturers to the world of third-party software applications – including MATLAB. The applications developed in the Windows NT environment provide the user with a high level of comfort, a user-friendly Graphical User Interface, and are a preferred way to add advanced control, optimization and visualization applications to distributed control systems.

Rapid prototyping in MATLAB/Simulink

To verify the feasibility of the novel model-based predictive control, prototype solution was developed using MATLAB and Simulink. The process is modeled by a time-invariant *n* th-order MIMO ARX model in the positional form

$$y(k) = -\sum_{i=1}^{n} A_i y(k-i) + \sum_{i=0}^{n} B_i u(k-i) + \sum_{i=1}^{n} C_i v(k-i) + e(k)$$

where *u(k)* a vector of manipulated inputs, *v(k)* is a vector of disturbances (measurable or predicted), *y(k)* is a vector of outputs, and *e(k)* is a white noise sequence of measurement noise and. *A*, *B*, *C* are coefficient matrices of appropriate dimensions. To predict the process output for the prediction horizon $k, k+1, \ldots, k+N$, we can write the model equations using known data up to time k-1 in a compact form

$$\left[\mathbf{A}_s \;\vdots\; \mathbf{A}\right]\begin{bmatrix} y(k-n) \\ \vdots \\ y(k-1) \\ \hline y(k) \\ \vdots \\ y(k+N) \end{bmatrix} = \left[\mathbf{B}_s \;\vdots\; \mathbf{B}\right]\begin{bmatrix} u(k-n) \\ \vdots \\ u(k-1) \\ \hline u(k) \\ \vdots \\ u(k+N) \end{bmatrix} + \left[\mathbf{C}_s \;\vdots\; \mathbf{C}\right]\begin{bmatrix} v(k-n) \\ \vdots \\ v(k-1) \\ \hline v(k) \\ \vdots \\ v(k+N) \end{bmatrix} + \mathbf{d} + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \hline e(k) \\ \vdots \\ e(k+N) \end{bmatrix}$$

with the coefficient matrices having band structure

$$\left[\mathbf{A}_s \;\vdots\; \mathbf{A}\right] = \left[\begin{array}{ccc|cccccc} a_n & \cdots & a_1 & 1 & & & & & \\ & \ddots & & \vdots & \ddots & & & & \\ & & a_n & a_{n-1} & \cdots & 1 & & & \\ & & & a_n & \cdots & a_1 & 1 & & \\ & & & & \ddots & & \ddots & \ddots & \\ & & & & & a_n & \cdots & a_1 & 1 \end{array}\right]$$

Then, using a quadratic criterion for the tracking error and control increments, the criterion can be written as a standard QP problem

$$\min_{\mathbf{u},\mathbf{z},\mathbf{z}_\Delta} \tfrac{1}{2} \left\| \begin{bmatrix} \mathbf{S} & -\mathbf{I} & \mathbf{0} \\ \mathbf{DS} & \mathbf{0} & -\mathbf{I} \\ \mathbf{D} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{z} \\ \mathbf{z}_\Delta \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{y}} \\ \mathbf{D}\tilde{\mathbf{y}} - \mathbf{y}_0 \\ \mathbf{u}_0 \end{bmatrix} \right\|^2_{\begin{bmatrix} \mathbf{Q} & & \\ & \mathbf{Q}_{\Delta y} & \\ & & \mathbf{R} \end{bmatrix}}$$

subject to

$$\mathbf{y}_L \le \mathbf{z} \le \mathbf{y}_H$$
$$\Delta\mathbf{y}_L \le \mathbf{z}_\Delta \le \Delta\mathbf{y}_H$$
$$\mathbf{u}_L \le \mathbf{u} \le \mathbf{u}_H,\ \Delta\mathbf{u}_L + \mathbf{u}_0 \le \mathbf{Du} \le \Delta\mathbf{u}_H + \mathbf{u}_0$$

and solved using the QP solver. For the tuning of the prototype algorithm, also the prototype GUI was built using Matlab graphics (see Figure 6).

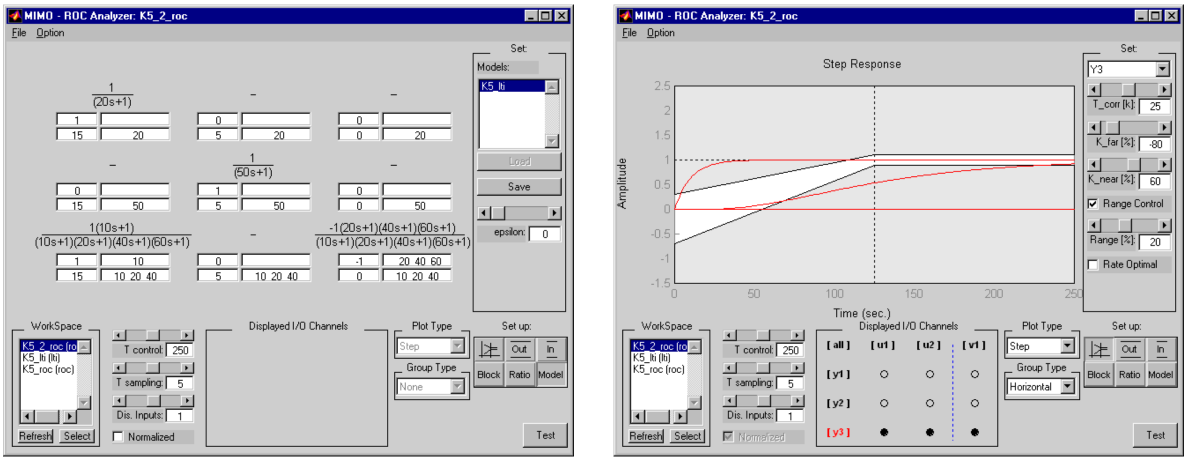

Figure 6. Prototype MATLAB GUI for model definition and controller performance specification

For the tuning of the ACC controller, boiler model implemented in Simulink was used (see Figure 7). The model was connected to the ACC Matlab prototype (implemented as an s-function) via RT toolbox TCP/IP driver.

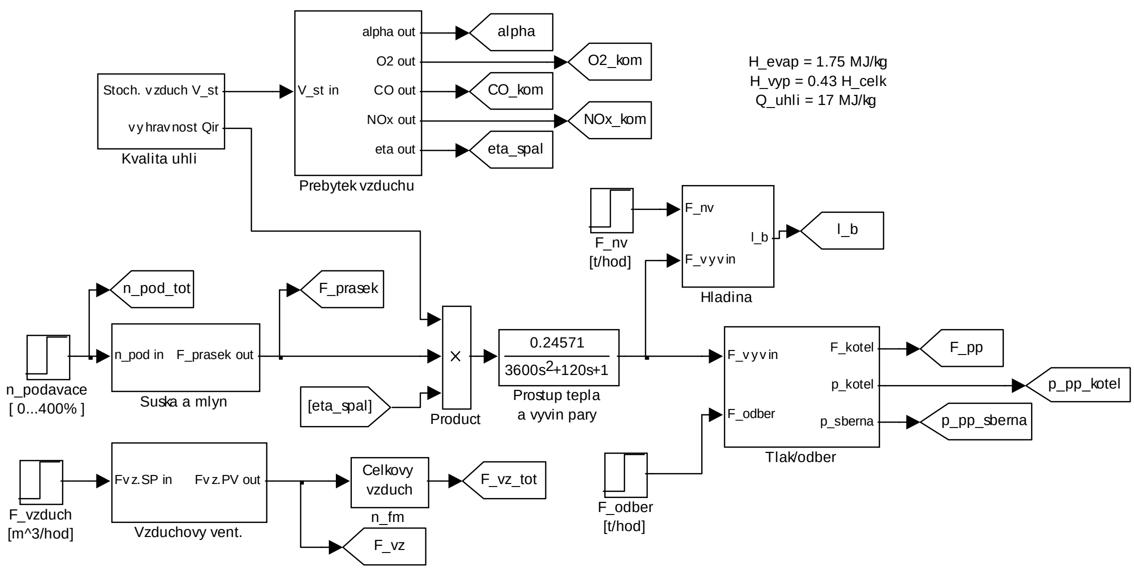

Figure 7. Boiler model implemented in Simulink

After the ACC Matlab prototype has been fully functional and pretuned using the model, the model was simply replaced by the real boiler. To enable real-time communication with the Honeywell distributed control system TPS, the functionality of the RT toolbox was extended – in cooperation with Humusoft - by a TCP/IP driver and HCI server. The RT toolbox HCI server is configured by an “ini” file to collect the required data points from the DCS and supply them via TCP/IP to the TCP/IP driver of the RT toolbox. A typical initialization file has to provide the following information:

```
[General]
RemoteAddress=194.212.236.76............. define the client address and port number
RemotePort=3190
LocalPort=3190
Servername=template_server1

[ReadGroup]
UpdateRate=1 ............................ define the sampling period
Write=0 ................................. define write/read group
DeadBand=0 .............................. define the signal change to initiate “OnDataChange” action
FirstPoint=1............................. define RT toolbox channel number

mroc1mv1.dmvp ........................... define the data point in the group
mroc1mv2.dmvp

[WriteGroup]
UpdateRate=1
Write=1
DeadBand=0
FirstPoint=1

mroc1mv1.smvp
mroc1mv2.smvp
```

Benefits

The Advanced Combustion Control applications provides a low-cost alternative to more expensive boiler retrofits for emissions reduction and operational profit improvement or further leverages the effect of primary DeNOx measures for retrofitted units. Performance measurements based on long term data comparison have shown that the lower excess air level can significantly reduce the NOx emissions levels and their variations (see Figure 8).

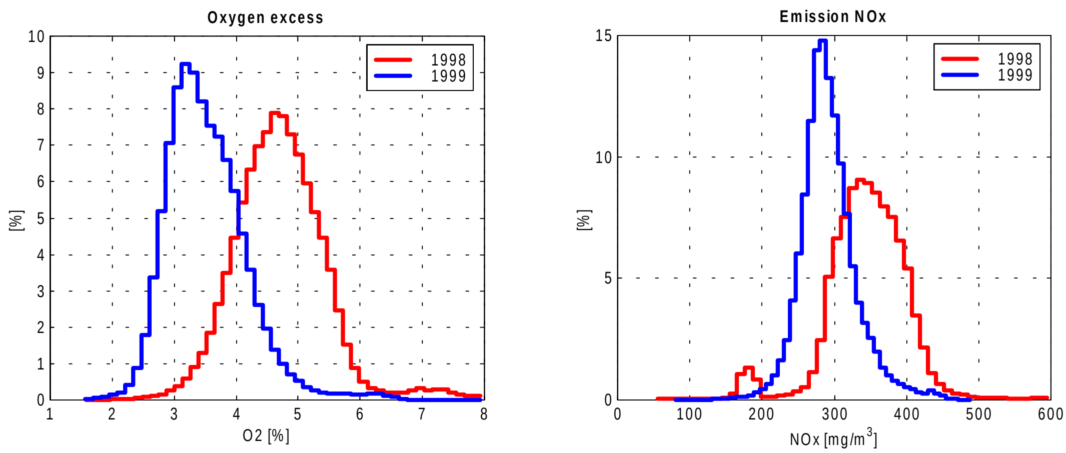

Figure 8. A comparison of the oxygen level and NO_x emissions

At the same time, the lower excess air level results in lower heat loss in flue gas which improves the efficiency by about 1 % (see Figure 9).

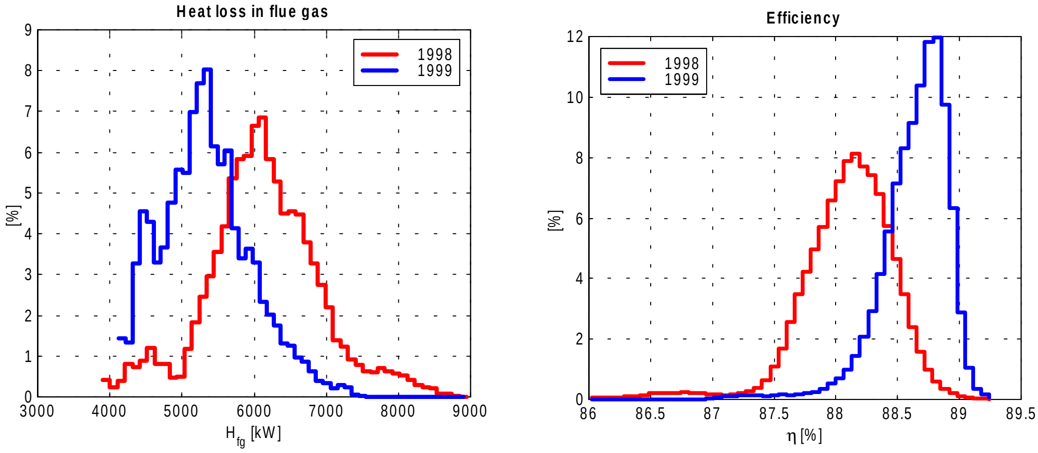

Figure 9. A comparison of heat loss in flue gas and efficiency

The comparison is based on one month data sampled at 6 s sampling rate. The tool for the evaluation of the data, collected by the PHD (Plant History Database) – as the typical Matlab graphics touch and feel suggests – was also developed in MATLAB.

Conclusion

The **Advanced Combustion Controller** became the basis for a new generation of products for power and heat generation control and optimization. Increased boiler efficiency and reduction of flue emissions will contribute considerably to the operating economy of DH Plant Otrokovice and to the improvement of the environment in the whole region.

The availability of the process data via OPC makes MATLAB an ideal platform for the development of remote monitoring and support tools, which are an important part of the emerging “e-business” in the field of advanced process control and optimization.

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