Stepan OZANA[1], Martin PIES[1], Luis VAZQUEZ[2]
VSB – Technical University of Ostrava (1), Universidad de Oriente (2)

Use of Methods of Statistic Dynamics Applied for Analysis of Steam Superheater

Abstract. *This paper deals with verification of the Simulink model of dynamics of control circuit with real control circuit operating in superheater of Detmarovice power plant. This is carried out by means of exploring reaction of output superheater's temperature to a disturbance signal, while the output regulated temperature is kept at constant value. The stochastic methods were used for evaluation of this nonlinear circuit. The last part of the paper is devoted to description of IME (Industrial Multivariate Explorer), which is graphical user interface for data visualization and basic analysis.*

Streszczenie. *Artykuł dotyczy weryfikacji Simulinkowego modelu dynamiki regulacyjnego obwodu z danymi zyskanymi z eksploatacji przegrzewacza w elektrowni Detmarovice. Odbywa się to poprzez analize reakcji temperatury na wyjściu z przegrzewacza na sygnał zakłócenia, podczas gdy temperatura na wyjściu jest regulowana na stały poziom. Stochastyczne metody zostały wykorzystane do oceny tego nieliniowego obwodu. Ostatnia część artykułu jest poświęcona opisowi IME (Industrial Multivariate Explorer), która jest graficznym interfejsem użytkownika do wizualizacji i analizy podstawowych danych.* ***(Użycie metod dynamiki statystycznej do analizy przegrzewacza pary)***

Keywords: identification, signal processing, superheater, statistic dynamics, Simulink
Słowa kluczowe: identyfikacja, przetwarzanie sygnału, przegrzewacz, dynamika statystyczna, Simulink

Introduction

The control circuit in Detmarovice power plant energetic block described in this paper consists of three cascading superheaters, each with its own main and fast control loop. Fast loop has to eliminate fast disturbances while a main loop serves for output temperature control. As the superheaters are divided into left and right parts, the experiments described here involve right section of the output superheater.

This control circuit includes concurrent superheaters together with the pipelines, referred to as unheated areas. These elements are described by partial differential equations (PDE)

[5] and by finite difference method transformed into the set of ordinary differential equations and then coded into Simulink S-functions as derived in [14]. For evaluation of the system agitated by stochastic signals and further identification, the mathematical models of superheater and unheated areas were used, considering constant steam flow through the system.

Control Circuit of Steam Superheater

The control circuit described in this paper is designed to keep the constant temperature of steam ($T_1(L,t) = 540°\mathrm{C}$) at the outlet of superheater. L stands for the length of superheater [m], t for time [s]. The output superheater consists of a pipeline which brings the steam into concurrent heat exchanger. The pipeline is modeled supposing the ideal isolation [4] (below referred to as unheated area). Principal scheme of the connection can be seen in Fig. 1.

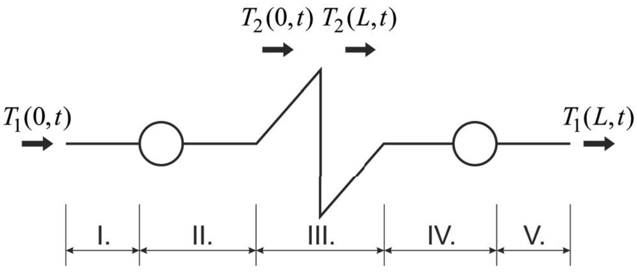


Fig. 1. Connection of unheated areas and concurrent steam superheater.

Mixer terms are described by algebraic equation (1):

$$M_{mix} \cdot h_{mix} = M_{wr} \cdot h_{wr} + M_v \cdot h_v, \quad (1)$$

where $h_w r(p, T_w r)$ a $h_v(p, T_v)$ stands for enthalpy of the water and water vapor. Mathematical model supposes the same pressure p for both media coming into the mixer.

Calculation of the enthalpies of media is carried out through tables of thermodynamic properties of water and water vapor according industry-standard IAPWS IF-97 [7].

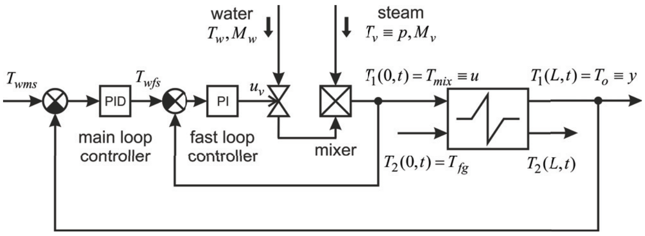


Fig. 2. Control circuit scheme for output superheater.

Fig. 2 shows the following signals measured under real operation and consequently used for running and verification of the simulation by use of the methods of statistic dynamic as follows: T_v steam temperature at mixer inlet, M_v steam quantity at the mixer inlet, T_{wr} water temperature at mixer inlet, M_{wr} water quantity at the mixer inlet, $T_{mix} = T_1(0,t)$ steam quantity at the mixer outlet, p steam pressure at the mixer outlet, T_{wms} desire temperature in main loop, constant, $T_{fg} = T_2(0,t)$ flue gas temperature, $T_o = T_1(L,t)$ superheater's output temperature.

It is necessary to determine the course of flue gas temperature, which cannot be directly measured due to the technological reasons. It is measured by other technological blocks that already affect the temperature course. Special algorithm was made up for calculation of flue gas temperature. Based on knowledge of temperatures T_{mix} and T_o it computes the flue gas temperature backward. Particularly it uses the splitting intervals method when the steady state of temperature T_o from simulation (hereafter denoted as T_{osim}) is compared with a temperature T_o measured under real operation. The temperature T_{osim} is a function of known (measured) steam temperature at the inlet of the superheater T_{mix} and working temperature T_{fg}, which is determined from a predefined interval. Based on given acceptable value of relative error between temperatures T_o and T_{osim} and its difference, the temperature T_{fg} is being refined until the relative error between T_o a T_{osim} is less than a given threshold. Resulting temperature T_{fg} and comparison of T_o and T_{osim} is given in Fig. 3. These two temperatures are almost identical because the comparison is carried out for

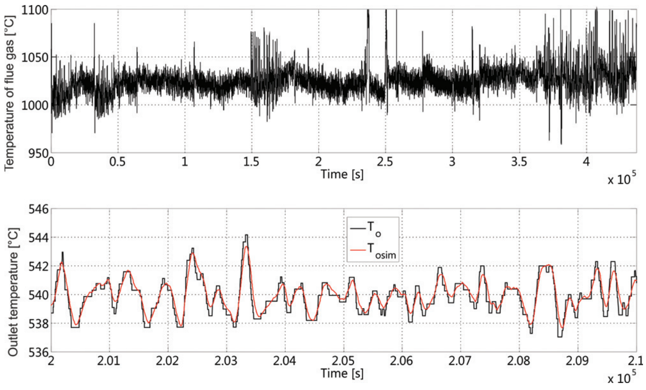


Fig. 3. Calculated flue gas temperature T_{fg} together with comparison of output superheater temperatures T_o a T_{osim}.

a setup with superheaters and unheated areas which is not involved in control circuit.

Measuring the plant by stochastic signals

Measured signals from real operation make up ten-day record from July/August 2009. The records are separated from daily periods when the power plant's wattage was 180MW, with sampling period of $T_s = 3$ seconds.

The control circuit (see Fig. 2) was fed with stochastic signals $T_v, T_{wr}, T_{fg}, M_{mix}$ a p_{mix}, measured in real operation. The following pictures show comparison of chosen signals from simulation and real operation. Fig. 4 compares output temperatures T_o and simulated T_{osimCL}. The difference

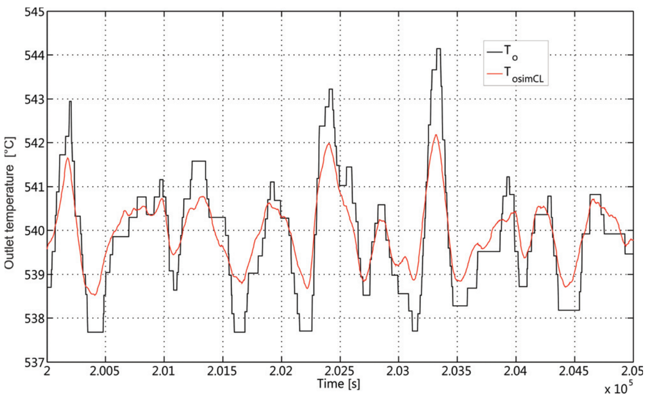


Fig. 4. Comparison of output temperatures T_o and T_{osimCL}, simulation of the whole control circuit.

compared to Fig. 3 is obvious. Temperature T_{mix}, coming into the superheater is no longer course from real operation, but simulated course control circuit consisting of simplified model of superheater and unheated areas. It causes differences between real and simulated data, as shown for valve opening positions in Fig. 5.

Measurements of correlation functions

Measurements of correlation functions of stationary stochastic signals is based on definition (2).

(2) $$R_{uy}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} y(t) \cdot y(t+\tau)\, dt$$

With respect to finite length of the record T_N and getting equidistant sample with sampling T_s, this formula can be transformed into summation

(3) $$R_{uy}[\tau] = \frac{1}{N - \frac{\tau}{T_s}} \sum_{k=0}^{N-\frac{\tau}{T_s}} y[t_k] \cdot u[t_k + \tau].$$

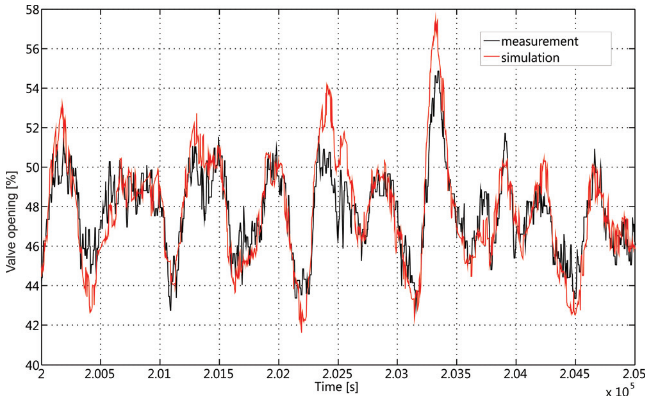


Fig. 5. Comparison of percentages of valve opening.

Values $y[t_k]$ and $u[t_k]$ stand for discrete samples of signals $y(t)$ and $u(t)$ in equidistant time intervals with T_s. Parameter N in equation (2) must be high enough since it is whole number of elements in record.

Reaching the solution requires choosing several parameters:

a) Whole length of measurement T_N must be quite long, so as all of the frequencies of the signals can be captured, especially lower ones. Calculation of autocorrelation functions for highest time shift τ_{max} requires

(4) $$T_N = (10 \div 20) \times \tau_{\max}$$

Calculating correlation functions according (3) for $\tau \neq 0$ causes distortion of resulting correlation function. This distortion grows with increasing distance from zero shift $\tau = 0$. That's why T_N is chosen the same size or bigger than the period of lowest importance elements of the signal according (4) to assure that distortion would for time much higher than τ_{max}.

b) Sampling time T_s must be so low to ensure that measured signals doesn't significantly change during T_s second. Once T_s is set, it's not possible to measure elements of signals with frequencies higher than:

(5) $$f_{\max} = \frac{1}{2T_s}$$

By means of the term (2) three correlation functions were calculated. First one is autocorrelation function of the signal that indicates detrended temperature of a steam at the inlet of mixer T_v. Other two correlation functions define time dependencies between detrended temperatures T_v, T_o and T_v, T_{osimCL}.

Ergodic hypothesis

Stochastic signal, as a name of continuous variable depending on time, can be stored in two different ways. It is either possible to make one record of infinite length or infinite number of finite length records. Despite the finite length of record of stochastic signal, infinite time interval is necessary to describe time dependence and sequence of the values. Ergodic hypothesis allows transition between these ways.

Due to the fact that length of the data to be processed would exceed the size of inverse matrix several times when computing numerical deconvolution, the whole record was divided into approximately 200 same time intervals. Then 200 correlation function of the same type were calculated and summed up, and the final result was divided by the number of intervals. Using this way, so called ergodic hypothesis has been implemented. As a result of this, the estimation of correlation functions was refined.

Identification the dynamics of control circuit with steam superheater

Method of identification the system by statistic dynamics is designed for linear systems. This paper describes its use for comparison of modeled control circuit in Simulink and real control circuit. The result of this identification is response of steam temperatures at the superheater outlet to Heaviside step of superheater inlet temperature. In simple words, it is response of the control circuit to step change of disturbance, representing steam temperature at the mixer inlet T_v.

When computing numerical deconvolution, Wiener - Hoppf equation

(6) $$R_{uy}(\tau) = \int_0^\infty h(t)\, R_u(\tau - t)\, dt$$

represents stochastic formulation of dynamic system. Under a special condition, in case of bringing white noise into input of the system having the following autocorrelation function

(7) $$R_u(\tau) = \delta(\tau),$$

we get

(8) $$R_{uy}(\tau) = \int_0^\infty h(t)\, \delta(\tau - t)\, dt = h(\tau)$$

Numerical calculation of weighting function is based on replacing integration process by summation and numeric deconvolution. Discretizing equation (8) leads to:

(9) $$R_{uy}(\tau) \approx \sum_{k=0}^{N} R_u(\tau - k \cdot T_s) h[k \cdot T_s] \cdot T_s$$

If time shift τ is expressed as multiple of time step T_s, that is $\tau = 0, T_s, 2T_s, \ldots, N$, it is possible, using the last equation, a set of $N + 1$ linear algebraic equations [9], from which it is possible to compute unknown values of weighting function $h(0), h(T_s), \ldots, h(NT_s)$.

Using following feature of autocorrelation function $R_u(\tau) = R_u(-\tau)$ and after introduction of shortened notations of weighting function $h_k = h[kT_s]$ and $R_x[k] = R_{xx}[kT_s]$, the set of equation can be rewritten into matrix form (10).

(10)
$$\begin{bmatrix} \frac{R_{uy}[0]}{T_S} \\ \frac{R_{uy}[1]}{T_S} \\ \vdots \\ \frac{R_{uy}[N]}{T_S} \end{bmatrix} = \begin{bmatrix} R_u[0] & R_u[1] & \cdots & R_u[N] \\ R_u[1] & R_u[0] & \cdots & R_u[N-1] \\ \vdots & \vdots & \ddots & \vdots \\ R_u[N] & R_u[N-1] & \cdots & R_u[0] \end{bmatrix} \times \begin{bmatrix} h_0 \\ h_1 \\ \vdots \\ h_N \end{bmatrix}$$

Or in the matrix form.

(11) $$\mathbf{r} = \mathbf{R} \cdot \mathbf{h}.$$

Solution of weighting function can be reached by use of inverse matrix $\mathbf{R}^{-1}$ as follows:

(12) $$\mathbf{h} = \mathbf{R}^{-1} \cdot \mathbf{r}.$$

This numerical solution of deconvolution in Matlab is limited by matrix until approximately elements.

Concerning that the length of measured data exceeds the size of the matrix that would be created during numerical solution of deconvolution, it is suitable to split the record into several same sections and compute particular impulse characteristics. The second reason for splitting is the fact that time constant of superheater is smaller than time of calculated impulse response that would be computed in case of maximal possible solution of numeric deconvolution ($3000 \times T_s = 9000$ seconds). Due to this reason, the ergodic hypothesis was used for estimation of impulse characteristic. Applying numerical deconvolution of Wiener - Hopf

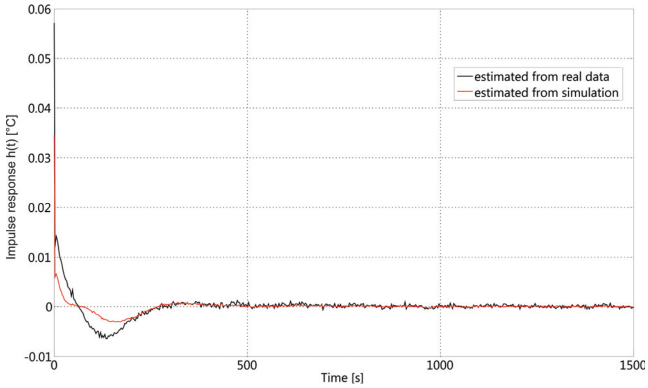


Fig. 6. Comparison of estimations of impulse characteristics of disturbance transfer function.

equation (6) leads to estimation of impulse characteristic of disturbance transfer function (see Fig. 6). In equation (6) signal u denotes temperature T_v and signal y stands for temperature T_o, resp. T_{osimCL}. To get worked this method in proper way it is necessary to detrend the temperatures. Integrating impulse characteristic we get estimation of the step response of disturbance transfer function (see Fig. 7).

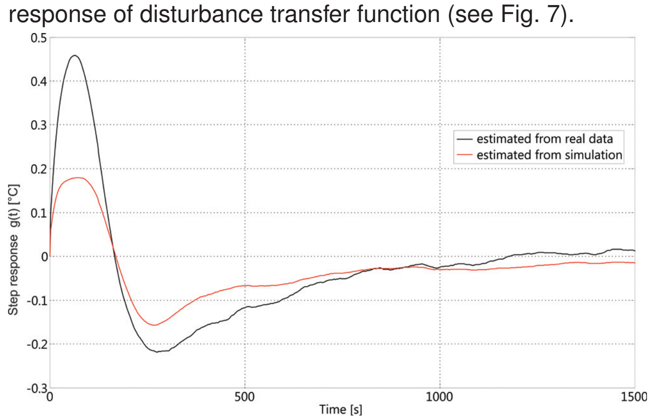


Fig. 7. Comparison of estimations of step characteristics of disturbance transfer function.

Disturbance transfer function figuratively means “black box” systems representing modeled control circuit, see Fig. 2. This control circuit compensates error corresponding to steam temperature at the inlet of mixer T_v. Fig. 7 shows comparison of estimated step responses. The first one is computed from measured data while the second one is calculated from simulation of modeled control circuit driven by measured data. Evaluating dynamics of these responses, it is possible to conclude that real control circuit has very similar dynamic as its model. The difference overshoot can be resolved by the fact that temperatures T_v and T_o are correlated to a certain degree. The steam of temperature T_v which is brought into mixer, is output product of previous second degree of the superheater. This superheater is heated with the same flue gas as the output superheater described in this paper. It results in affecting estimation of impulse, resp. step response of the circuit. In case of the comparison the result of this identification with the response to the Heaviside step, it would be necessary to change the flue gas temperature proportionally to the value of the step at the mixer inlet, with adequate advanced time interval corresponding to the soaking all of the superheaters so that inlet mixer temperature rises by $1°\mathrm{C}$.

A computing solution to monitor in short and long therm

Explorer of Process Industrials (EPI) was developed in Matlab for Felton Power Plant [16, 17]. Their steam generators for two blocks, each one of 250 MW, were made by SES TLMACE (Slovenske Energeticke Strojarne) company. EPI is developed by a set of user graphical interfaces. Each one handles a set of variable corresponding to historical variables that were exported from a supervisory computer. Using two cursors on the main graphical EPI interface, the user chooses a short window of the signal corresponding to a steady state. Choosing each graphical interface makes it possible that a different computing task can be performed on each group of variables and results to be saved into Excel file. Among them, it can be listed the following ones: thermal energy transferred to water/steam through several heat transfer exchanging surface into steam generator, fuel overconsumption indexes calculation, etc.

Also, the second version has been developed, but the user's interface is not associated to any specific power. It is called as Industrial Multivariate Explorer. It makes it possible to perform data analysis on long time windows. IME saves its computed data into a Secondary Data Base (SDB). Data comes into IME by a Primary Data Base (PDB). It consists of a time series set exported from an existing supervisory computer in the power plant. These features promoted its application on EDE power plant from Czech Republic.

When a system submitted to thermodynamic transformations is not steady, thermodynamic system parameters are highly unstable. Some of the first investigations of system steady-state identification came from process control field studies [11, 2, 8, 10, 13].

Bad functioning of these control structures affects the power plant operation, [12]. The data available from plant sensors supplied to the control systems may also be analyzed to verify proper operation and to predict future behavior, [3]. Specific methods, for power plant monitoring and diagnosis, are currently being researched. For instance, for monitoring of practical flames [1], monitoring applications in nuclear power plants [6], thermo-economic diagnosis of the operation [15].

There are three following IME' features, (see Fig. 8). To visualize up to 8 time series linearly normalized in amplitude and distributed on the plot, to choose a sub-set of vector's components enclosed between two cursors (see Fig. 10) and to save into a Secondary Data Base (SDB) with the value of some statistics computed to set of elements chosen between cursors of each variable from a Primary Data Base (PDB), (see Fig. 11).

Application of IME to EDE Power Plant

IME aids to a simulated experiment for fouling detection into EDE Superheater experimental setup. Essays were performed by the closed loop temperature control scheme, shown in Fig. 2, running on a simplified model of experiment setup. The fouling effect was introduced on α_{S2} parameter changes into S-function of the Superheater, see Fig. 9. As it should be expected, the control system (set up by 2 PID controllers) is able to keep, in steady state the steam outlet

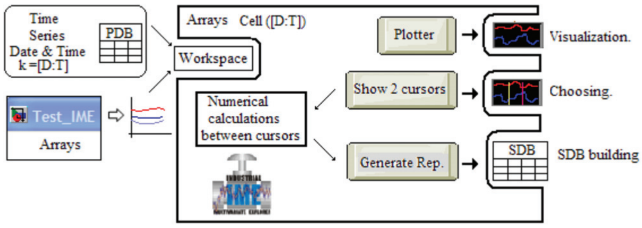


Fig. 8. IME's features

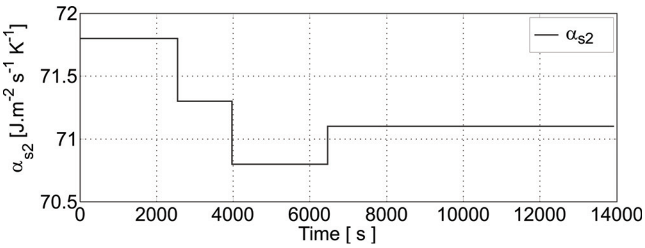


Fig. 9. Time sequence on α_{S2} changes which are introduced into S-function Superheater.

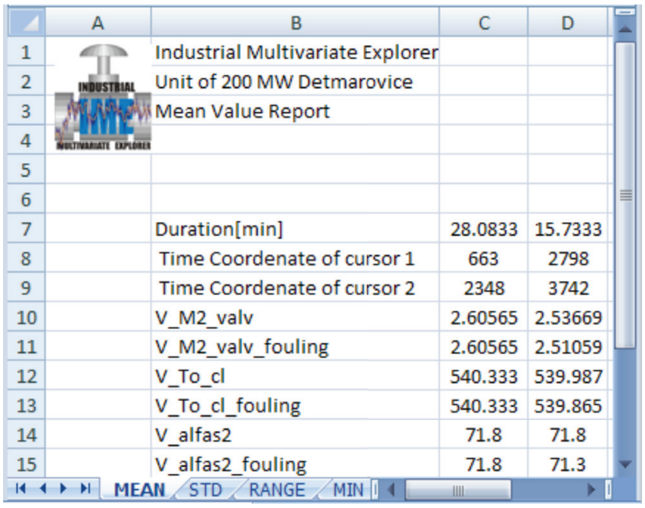
temperature on like value, both without/and with fouling effect. Nevertheless , "M_{wr}" signal, i.e., water quantity at the mixer inlet have to changes when α_{S2} changes. Indeed, α_{S2} changes modify transferring energy course from flue gas to superheated steam. In Fig. 10 by a single look at the records on both M_{wr} responses it is not possible to detect changes. Its waveforms are very like. Also, in a current industrial operation it only is recorded one response. Nevertheless, M_{wr} mean values on lengthen time windows are different.

In Fig. 10, first record (yellow) corresponds to a time sequence on α_{S2} changes like to shown in Fig. 9. User is in charge to detect the time window where a quasi steady state exists. In this example, it is easy to choose α_{S2} without/with changes. IME's SDB permits to save on Excel file the new M_{wr} mean results, see Fig. 11. With this Long Time Window data base is now possible to assess fouling effects on the superheater's surface.

In particular three M_{wr} mean values are plotted in Fig. 12. Supported of scheme in Fig. 2 are performed two experiments: without fouling through α_{S2} = 71.8 Jm^{-2}K^{-1}s^{-1} and by fouling modulation by a time sequence on α_{S2} changes shown in Fig. 10. To assess the α_{S2} changes effect on M_{wr}, by the two cursors, three time window are chosen as follow: [663 2348], [2685 6326] and [9629 11315]. On the first one, both simulated operation run without fouling, in the second chosen window, it has been introduced two α_{S2} step changes and lastly in the third window it has been introduced α_{S2} change with a value higher than previous one.

Fig. 10. Main IME interface. Steady states choices by two cursors.

The goal is to exemplify the effect on this parameter, once time a soot blowing operation has been carried out. Indeed the efficiency transferring energy course from flue gas to superheated steam has improved by fouling reduction.



	A	B	C	D
1		Industrial Multivariate Explorer		
2		Unit of 200 MW Detmarovice		
3		Mean Value Report		
4				
5				
6				
7		Duration[min]	28.0833	15.7333
8		Time Coordenate of cursor 1	663	2798
9		Time Coordenate of cursor 2	2348	3742
10		V_M2_valv	2.60565	2.53669
11		V_M2_valv_fouling	2.60565	2.51059
12		V_To_cl	540.333	539.987
13		V_To_cl_fouling	540.333	539.865
14		V_alfas2	71.8	71.8
15		V_alfas2_fouling	71.8	71.3

MEAN STD RANGE MIN

Fig. 11. SDB to assess fouling effects on Superheater's surface.

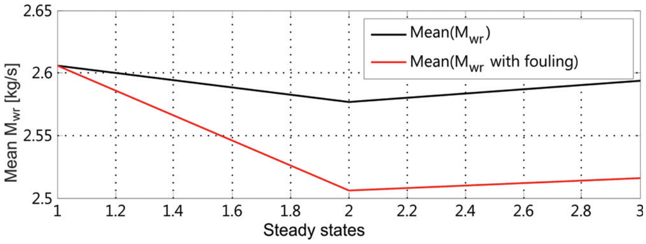


Fig. 12. M_{wr} Mean values sequence with and without fouling effect over superheater surface.

Conclusion

Both superheater and unheated area are modeled as distributed-parameter systems which makes it possible to estimate the course of temperatures not only at the output but at any point of supeheater. Due to this fact, the designers are able to tune the parameters of superheaters and control circuit so that the strain of the superheater and its other parameters are kept within the safe technological ranges. Tha basic tool called Industrial Multivariate Explorer was created to provide easy data visualization and analysis, using the strong computational capabilities of Matlab&Simulink environment. Identification by the method of statistic dynamics in this case clarified approximated compliance between modeled and real control circuit. To a great extend it is caused by statistic dependence of inlet mixer temperature T_v and output superheater temperature T_o. Both of these temperatures are to a certain degree correlated by flue gas temperature, whose time course is unknown because it's not measure under real operation. For comparison purposes the flue gas temperature time course was computed backward based on analytical model of output superheater.

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Authors: Ing. Štěpán Ožana, Ph.D., Ing. Martin Pieš, Department of Measurement and Control, Faculty of Electrical Engineering and Computer Science, VSB – Technical University of Ostrava, 17. listopadu 15, 70833 Ostrava, Czech Republic, email: stepan.ozana@vsb.cz, M. Sc. Ing. Luis Vázquez, University of Oriente (Sede Mella), Faculty of Electrical Engineering, Ave Las Americas S/N. Esquina Casero, 90400 Santiago of Cuba city, Cuba, email: lvazquez@fie.uo.edu.cu