Variations in flue gas of power plant heat exchanger and their determination with the assistance of the mathematical model

PIES MARTIN, OZANA STEPAN, NEVRIVA PAVEL
Department of Measurement and Control, Faculty of Electrical Engineering and Computer Science
VSB – Technical university of Ostrava
17. listopadu 2172/15, 708 33 Ostrava
CZECH REPUBLIC
martin.pies@vsb.cz http://fei.vsb.cz

Abstract: - High temperature heat exchangers of a power plant boiler are nonlinear MIMO systems with distributed parameters. They transfer heat energy from flue gas to steam. The design and construction of a power plant boiler is affected by fluctuations in temperature, flow rate, pressure and other physical quantities of steam and flue gas in its heat exchangers. Time waveforms of these fluctuations are functions of length and time and are not measured along heat exchanging surfaces of heat exchangers. In the heat exchanger, the global influence of different flue gas fluctuations to the output steam temperature fluctuations can be expressed by a flue gas virtual temperature noise. Flue gas virtual temperature noise is a function of length and time that represents the global temperature influence of flue gas random variations. The determination of the flue gas virtual temperature noise waveform with the assistance of the mathematical model of the heat exchanger assembly is presented in the paper. Both the algorithm and the mathematical model work with data generated by the standard technological process. Resulting waveforms obtained by simulation are compared by measurements.

Key-Words: - MIMO systems, systems with distributed parameters, PDE, heat exchangers, temperature noise, signal analysis, simulation

1 Introduction

The general goal of power plant control is to optimize the efficiency of electric power generation. It means to master mathematical description of local units of power plant energy circuits.

For further discussion we choose conventional coal power plant operating with superheated steam. The power plant burns in the first stage of boiler the coal and generates flue gas and saturated steam. The saturated steam is led to heat exchangers. Heat exchanger transfers heat energy from flue gas to steam. It can be made as a bundle of steel tubes by which flows steam, submerged into the stream of flue gas. The walls of tubs create heat exchanging wall of the heat exchanger.

The power plant has usually many heat exchangers. The system studied in this paper is the high temperature output heat exchanger, superheater, SH, that generates superheated steam of defined temperature. At coal power plants, it is about 540 °C.

The SH can be described as a MIMO unit that has two inputs and two outputs. The inputs are the input of the saturated steam and the input of the hot flue gas. The outputs are the output of the superheated steam and the output of the cold flue gas.

Steam is lead to/from the SH by an inlet/outlet piping, see Fig. 1. Temperature of steam at the input and output of the SH is controlled by temperature controllers. These blocks define so called superheater assembly, SHA.

![Fig. 1 Superheater (SH) with pipelines (PL)](image)

Long time analysis of measured data shows that under the stabilized operating conditions of a power plant the time waveforms of temperatures of steam have the constant values of temperatures that are disturbed by temperature noises. These noises have the Gaussian distributions. To obtain sufficient
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Another registered temperature waveforms were temperature of water injected to the inlet steam and temperature set point value. All measurements were made with the constant sampling interval of 3 seconds.

Thermal noise has the Gaussian distribution. According to measurements of temperature, measured and calculated noises were as follows. The noise of temperature of steam at the input of the SH input (input steam noise \( n_i(0,t) \)), the noise of temperature of steam at the inlet of the SHA (inlet steam noise \( n_1(I,t) \)), and the noise of temperature of steam at the output of the SH (output steam noise \( n_1(L,t) \)). The noise \( n_i(x,t) \) is the temperature drift of the heat exchanging wall. It is calculated by the model.

Noise signals \( n_i(I,t) \), \( n_i(0,t) \) and \( n_1(L,t) \) were tested on stationary. Fig. 3 shows the variances of 100 successively obtained populations of measured data of \( n_i(I,t) \). Every population contains 1500 members. Populations corresponding to the steady state power plant production of 200 MW are accepted by the model. In Fig. 3, the populations that are accepted by the model are assigned by gray color.

The average value of variance of the inlet steam noise \( n_i(I,t) \) was 1.50 ± 0.31 °C². The average value of variance of the input steam noise \( n_1(0,t) \) was 1.05 ± 0.18 °C². The average value of variance of the output steam noise \( n_1(L,t) \) was 1.25 ± 0.33 °C².

2 Mathematical models of a superheater and pipelines

Both the SH and pipelines are nonlinear MIMO systems with distributed parameters. Controllers are composed from both nonlinear and linear blocks.
with lumped parameters. Systems of similar structure are in action in many thermal power plants.

Dynamical behavior of the SH can be described by a set of nonlinear partial differential equations. Dynamical behavior of pipelines can be described by the sets of linear partial differential equations. Controllers and associated equipment are described by ordinary differential equations and algebraic equations. Parameters of all these blocks are known with fairly good accuracy.

The linear model of thermal dynamics of SH is described by (1). The model (1) is useful in routine simulations of temperature processes on SH. Model works with absolute values of physical quantities. Some of them can be measured. Some of them are set by the designer’s heat balance. Model assumes knowledge of flow rates. In standard simulations, the fluctuations of physical quantities can be omitted.

$$T_W - T_1 = \tau_1 \left[ u_1 \frac{\partial T_1}{\partial x} + \frac{\partial T_1}{\partial t} \right]$$

$$T_W - T_2 = \tau_2 \left[ u_2 \frac{\partial T_2}{\partial x} + \frac{\partial T_2}{\partial t} \right]$$

$$T_1 - T_W = \frac{\tau_W}{\alpha_W} \left[ \alpha_W \frac{\partial T_W}{\partial x} \right]$$

(1)

Where

$$\tau_1 = \frac{c_1 M_1}{\alpha_W |O_1|}, \quad \tau_2 = \frac{c_2 M_2}{\alpha_W |O_2|}, \quad \tau_W = \frac{c_W G}{\alpha_W |O_1|}$$

Parameters of the model specify the dynamics of the heat exchange in SH are shown in Table 1.

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>heat capacity of steam</td>
<td>J·kg⁻¹·K⁻¹</td>
</tr>
<tr>
<td>$c_2$</td>
<td>heat capacity of flue gas</td>
<td>J·kg⁻¹·K⁻¹</td>
</tr>
<tr>
<td>$c_W$</td>
<td>heat capacity of superheater’s wall material</td>
<td>J·kg⁻¹·K⁻¹</td>
</tr>
<tr>
<td>$G$</td>
<td>heat exchanging wall per unit of its length in x direction</td>
<td>kg·m⁻¹</td>
</tr>
<tr>
<td>$L$</td>
<td>active length of the wall</td>
<td>m</td>
</tr>
<tr>
<td>$M_1$</td>
<td>steam flow rate</td>
<td>kg·s⁻¹</td>
</tr>
</tbody>
</table>

Table 1 Superheater parameters

In a superheater, flue gas heats steam. In a pipeline, steam warms the surrounding air. In consequence, the mathematical model of a pipeline is given by the same system of equations. The flue gas has to be substituted by air. For an insulated pipeline, the thermal losses to the external environment can be often neglected. Then, $\alpha_W \rightarrow 0$ and the mathematical model of pipeline can be reduced.

The PDE can be solved by many methods. Equations have two independent variables. They are space variable length $x \in [0, L]$ and time $t \in [0, \infty)$. Here, the method of finite differences was used. The method was modified to facilitate the simulation of control problems. Every PDE was approximated by the set of 30 ordinary differential equations, ODE. The independent variable of ODE is time. Integration of the set of ODE by Euler method, Runge-Kutta methods, a linear multistep method, or any other standard numerical formula can be applied. The methods cover here the advantages of the finite element method and are applicable to the simulation of the complex power plant control problems. In this work, the MATLAB Stiff/NDF formula was used.

3 Virtual noise of flue gas

Fluctuations in both temperature and flow rate of flue gas are input signals that are functions of two independent variables length and time. They cannot be measured along the heat exchanging surfaces of SH with sufficient accuracy. To deal with
fluctuations, the standard procedure has to be modified.

The linear model (1) can be easily adapted to the linear model describing the agitation of the SH by the virtual noise \( n_v(x,t) \). Fig. 4 shows the principal scheme of the superheater assembly with the SH described by the noise model (2).

The resulting relationships are (2).

\[
\begin{align*}
W-W_1 &= \tau_1 \left[ u_1 \frac{\partial n_1}{\partial x} + \frac{\partial n_1}{\partial t} \right] \\
W-W_2 &= \tau_2 \left[ u_2 \frac{\partial n_v}{\partial x} + \frac{\partial n_v}{\partial t} \right] \\
\frac{n_1-n_W}{\tau W_1} + \frac{n_v-n_W}{\tau W_2} &= \frac{\partial n_V}{\partial t}
\end{align*}
\]

(2)

The SH and its dynamics of SH remains unchanged. Parameters of the model (2) are the same as those of model (1).

The input virtual noise waveform \( n_v(0,t) \) has to be determined from the waveforms of the input steam noise \( n_1(0,t) \) and the output steam noise \( n_1(L,t) \) that are measured and calculated at the actual SHA.

The problem lies in the existence of correlated noise between flue gas and steam.

The fluctuations in flue gas act as a primary source of noise in the system. A part of this noise is transferred with different intensity into temperature of steam. The temperature noise of steam in any part of SH is thus time correlated with flue gas noise and with temperature noises in the other parts of SH. To study the impact of flue gas noise on the output steam noise \( n_1(L,t) \), the input steam noise \( n_1(0,t) \) has to be taken into account. Flue gas noise, input steam noise \( n_1(0,t) \), and output noise \( n_1(L,t) \) are correlated. Calculation of \( n_1(0,t) \) has to be done deterministically.

The mathematical model of the SHA was constructed and implemented on computer and the deterministic waveform of the input virtual noise \( n_v(0,t) \) at the input of SH was calculated numerically.

For technical reasons, temperatures \( T_1(0,t) \) and \( T_1(L,t) \) are not measured at the inlet and outlet of the steal bundle of the SH. They are measured at inlet and outlet pipelines at some distance from SH. To generate the waveform sufficiently long in reasonable time, mathematical model was simplified for the calculation. The adjacent parts of the inlet and outlet piping of the SH were removed from the model.

Every discrete value of waveform of \( n_v(0,t) \) was obtained from the measured discrete values of both the input steam noise \( n_1(0,t) \) and the output steam noise \( n_1(L,t) \) by iterative calculation. Then, the resulting \( n_v(0,t) \) was tested on the full model of SHA. Fig. 5 shows that the calculated input virtual noise \( n_v(0,t) \) generates, with the measured input steam noise \( n_1(0,t) \), the simulated output steam noise waveform \( n_1(L,t) \) close to the measured signal.

All temperatures discussed are stabilized at their operating points. All are corrupted with additive temperature noise. Fig. 7 compares the cross-correlation function \( R_{\overline{\overline{L}}}(0,t) \).
\[ R_{i(l)1(l)}(\tau) = \frac{1}{N_d} \sum_{i=0}^{N_d} n_i(l,t) n_1(l,t+\tau), \quad (3) \]

between measured inlet steam noise \( n_i(l,t) \) and simulated output steam noise \( n_1(L,t) \) with the cross-correlation function between measured inlet steam noise \( n_i(l,t) \) and measured output steam noise \( n_1(L,t) \).

Fig. 6 Comparison of the cross-correlation functions \( R_{i(l)1(l)}(\tau) \)

Fig. 7 compares the the correlation function \( R_{11}(\tau) \) of output steam noise \( n_1(L,t) \) obtained by simulation with the the correlation function \( R_{11}(\tau) \) of output steam noise \( n_1(L,t) \) obtained by measurement.

Fig. 7 Comparison of the correlation functions \( R_{11}(\tau) \)

Fig. 8 shows the correlation function \( R_{v0}(\tau) \) of input virtual noise \( n_v(0,t) \). Fig. 9 shows the amplitude spectrum \( |N_v(0,\omega)| \) of input virtual noise \( n_v(0,t) \).

Fig. 8 Correlation function \( R_{v0}(\tau) \) of input virtual noise \( n_v(0,t) \)

Fig. 9 Amplitude spectrum \( |N_v(0,\omega)| \) of input virtual noise \( n_v(0,t) \)

4 Conclusion

The heat exchanger can be described by a MIMO system with distributed parameters that is agitated by both the signals and the disturbance with distributed inputs.

The paper describes a novel method of determination of variations in flue gas of power plant heat superheater with the assistance of the mathematical model of heat exchanger.

The global influence of the flue gas variations to the heated steam temperature noise is expressed by the flue gas virtual temperature noise \( n_v(x,t) \).

To find the waveform of \( n_v(x,t) \), the mathematical model of heat exchanger is used to calculate the time waveform of input virtual noise \( n_v(0,t) \) from measured discrete data. The function \( n_v(x,t) \) is found by simulation.

Iterative calculation of the input temperature noise \( n_v(0,t) \) is based on values of both the input steam noise \( n_1(0,t) \) and the output steam noise \( n_2(L,t) \).
To determine the waveform \( n_v(0,t) \) the simplified model of superheater was used. The resulting \( n_v(0,t) \) was tested on the full model of superheater assembly.

Algorithm cooperates with the power plant that runs in operating conditions.

Measured waveforms were tested by statistical methods. Selected characteristics of the complete superheater assembly were calculated. Amplitude spectrum \( |N_v(0,\omega)| \) of the flue gas virtual temperature noise \( n_v(0,t) \) was found.

Theoretical results were tested by measurements at Detmarovice coal-fired power plant CEZ 4×200 MW. Selected experimental and simulation results are presented in the paper.

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