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Transfer function matrix model of the bubbling fluidized bed boiler

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Abstract The paper presents proposal of a model of the fluidized bed boiler adapted for use in model-based controllers e.g. predictive, adaptive or internal model control (IMC). The model has been derived in the form of transfer function matrix which allows its direct implementation in the controller structure. Formulated model takes into consideration the principal cross-coupling between process variables which enables the opportunity to search for feasibility of decoupling control. The results of the identification of the dynamics of the 2 MW industrial bubbling fluidized bed boiler using the proposed model form was presented. According to the experimental data it was found that despite of introduced simplifications presented model allows the boiler behavior prediction.

Keywords: Bubbling fluidized bed boiler; Transfer function matrix; System identification

Nomenclature

c_f	–	specific heat of fuel, kJ/kg K
c_p	–	specific heat of air, kJ/kg K
c_b	–	specific heat of bed material, kJ/kg K
c_g	–	specific heat of dry flue gas, kJ/kg K
$\dot{H}_f$	–	enthalpy flux of fuel and its moisture, kJ/s

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H_0	–	enthalpy of water (ambient temperature), kJ/kg
$H_{\theta b}$	–	enthalpy of steam (bed temperature), kJ/kg
m_b	–	bed mass, kg
$\dot{m}_p$	–	primary air mass flow, kg/s
$\dot{m}_f$	–	fuel feed rate, kg/s
M_g	–	mass of dry flue gas generated from 1kg of burned fuel, kg/kg
n_e	–	rotation speed of the exhausting fan, $\%n_{e\_max}$
n_f	–	rotation speed of the fuel feeder, $\%n_{f\_max}$
P_c	–	pressure in the combustion chamber, Pa
ΔP_b	–	pressure drop across the bed, kPa
Q_c	–	higher heating value of the fuel, kJ/kg
$\dot{Q}_a$	–	rate of heat of ash leaving bed, kW
$\dot{Q}_r$	–	radiative rate of heat, kW
$\dot{Q}_b$	–	rate of heat of combustion process in the bed, kW
$\dot{Q}_g$	–	rate of heat of flue gas, kW
$\dot{Q}_w$	–	rate of heat forwarded to the water in the waterwalls, kW
$\dot{V}_a$	–	primary air flowrate, m^3/s
x_b	–	fraction of a fuel combusted in bed
x_d	–	fraction of ash leaving the bed through the ash remover
X_a	–	ash content in the fuel
X_m	–	moisture content in the fuel

Greek symbols

α_b	–	heat transfer coefficient on surface of waterwalls surroundings the bed, W/m^{2}K
θ_0	–	ambient temperature, °C
θ_b	–	bed temperature, °C
θ_{wi}	–	water temperature at the inlet to the boiler, °C
θ_{wo}	–	water temperature at the outlet from the boiler, °C
θ_w	–	average temperature of the water-wall surface, °C

1 Introduction

In small, autonomous heating systems (e.g. for housing estate or factory) fluidized bed boilers are increasingly being considered nowadays as an alternative to withdrawals from the use of stoker-fired boilers. As the main reason is thought to be the possibility of efficient combustion of low quality (and therefore cheap) fuels while reducing emissions of substances such as SO_2 and NO_x to the atmosphere. In prospect of rising fuel prices and rigorous requirements for emission standards, these advantages can contribute to dissemination of this technology.

High quality of combustion in a fluidized bed defined as efficiency maximization at the lowest possible emission rates is expected to be provided by properly designed and tuned automatic control system. The controller synthesis problem in this case is especially complex. In particular: interaction between variables, nonlinearity or potential of process non-stationarity are the main causes that applying of the classic algorithms of process control (e.g. proportional-integral-derivative – PID) cannot show good results.

2 Fluidized bed boiler as the controlled system

Industrial fluidized bed boilers have to be equipped with a reliably functioning system of monitoring and automatic control [1,2,6]. It is connected with the need to maintain the process parameters in relatively narrow limits. The main difficulty in the design of the automation system is the cross-coupling between process variables, in particular phenomenon of a single input influence for more than one output. Serious problems can also be provided by uncontrolled changes in fuel properties (calorific value, moisture content). Fuels originating from wastes, sewage sludge or biomass are known to have highly variable properties. It is considered that these renewable fuels soon will gain particular significance therefore it is important to refine the technologies for their effective use. This justifies the need to search for advanced model-based process control algorithms for bubbling fluidized bed (BFB) boilers.

The most important, usually automatically controlled, process variables include:

- bed temperature,
- mass flow of the primary air,
- pressure drop across the bed,
- pressure in the combustion chamber,
- water temperature.

The lower limit of the bed temperature (700–750 $^{\circ}$C) is determined by increase emission of the CO and hydrocarbon (C_xH_y), and thus decrease the efficiency of energy conversion. There is also a possibility of interruption of combustion process. The upper limit of the bed temperature (950–1000 $^{\circ}$C) is the limit of ash melting point. Exceeding of this value threatens the possibility of formation the bed material agglomeration and even interrupt of the fluidization. Depending on the sort of fuel burned and additional process conditions (e.g. using reacting substances for desulphurization), this range may be further limited. For example, when limestone is used for flue gas desulphurization, bed temperature should be maintained at 850 °C because at this temperature sulfur capture efficiency is highest [1,2,6].

Control of the primary air flow is connected with the need to maintain the fluidization velocity within the limits determined by the critical speed (the beginning of fluidization) and, on the other hand, by the speed of pneumatic transport [1]. Pressure drop across the bed carries information about the mass of the bed material and, with fixed primary air flow, can be also used as measure of the bed height. This implies that this measurement can be used to control the discharge of excess bed material. For the process safety it is necessary to keep the pressure in the furnace slightly below atmospheric pressure, which is usually monitored by the appropriate sensor.

The water temperature is a crucial parameter in a fluidized bed boilers [6] used in area of district heating. Depending on the operating regime of automatic control (constant value, program-following, weather compensated) temperature should be maintained at a constant value, or keep up with changing the setpoint, determined by the supervisory system. Regardless of the control regime, water temperature dependence on several variables (bed temperature, bed height, primary air flow), while the volatility of demand for thermal power supplied by the boiler causes serious difficulties in the automatic control of this variable. Due to the difficulties of practical implementation of the water temperature controller, in small installations manual adjusting of this parameter can be often found but it usually results in significant oscillations. It is worth noting that obtaining good control of water temperature can reduce the investment costs during the construction of boilers by reduction of necessary capacity of buffering storage tanks.

Proper control of the above-mentioned variables is critical for safe and stable combustion process. It is necessary to draw attention to the existence of a number of interactions between controlled variables, which causes that the control loops marked on the drawing (Fig. 1) are in fact mutually coupled (via controlled system). This makes it necessary to take into considerations these dependencies in the design stage of the control system. Depending on the solution, there may be also a need for temperature measurements in the freeboard zone or the flue gas composition. Measurements of concentration of oxygen, CO, SO_2 and NO_x in the flue gas might be particularly important in determining the quality of the combustion process. Nevertheless, economic reasons causes that in small installations measurements of gas composition are hardly ever conducted on-line, but only during the test runs [1,6].

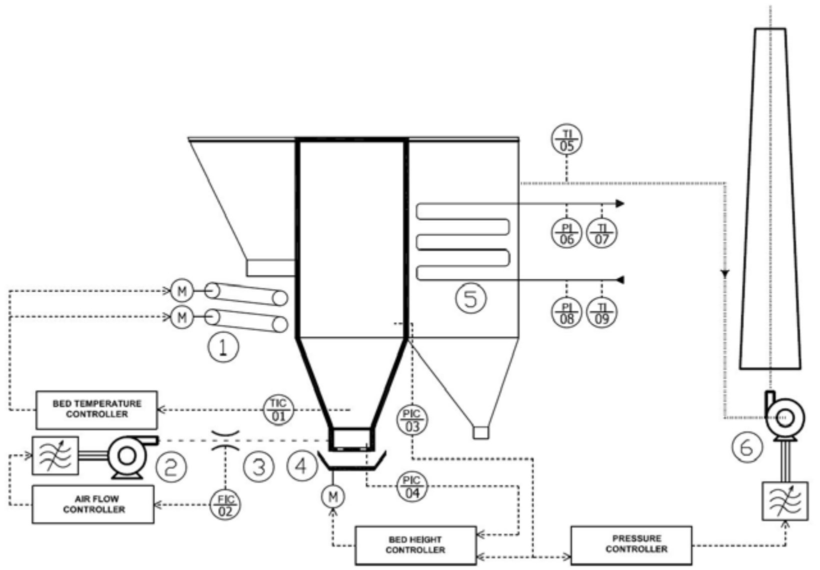

Figure 1. Diagram of a typical installation of low-power fluidized bed boiler.

The Fig. (1) shows the schematic of a typical installation of the low-power bubbling fluidized bed boiler. Fuel is feed into the bed by two independent feeders (1). Primary air pumped by the blowing fan (2) flows through the measuring orifice (3) and then goes to the air distributor. Excess of the bed material is drained through the ash remover (4). Water is heated in a water jacket surrounding the bed and the freeboard as well as in the heat exchangers (5). The exhaust gases are pumped into the chimney through the exhaust fan (6).

3 Dependencies between variables in the modeled boiler

Creating input – output model for the automatic control purposes is necessary to determine the assumptions associated with the construction of the boiler and its operating conditions as well as available measurements. In this study have been assumed that in the modeled boiler:

- there is no primary air preheater, it was assumed that air temperature is invariable,

- there are no feeding of inert material as well as SO_2 sorbents into the bed,
- water is heated both in the water jacket surrounding the combustion chamber, as well as in the heat exchangers,
- there are no measurements of flue gas flow, temperature and concentration of its compounds,
- parameters of the model must be able to be estimated on the basis of on-line measurements of physical parameters of the process,
- bed mass is constant — in typical operating conditions it does not change significantly.

These assumptions result from the construction and operating conditions of fluidized bed boiler with a capacity of 2 MW, which was used for experimental research.

Analyzing the bed temperature dependence from individual control variables, as well as disturbances it is necessary to consider the energy balance for the bed. The general form of the energy balance has been described in detail by Basu [1]. Equations (1)–(6) given below represent its adaptation to the specific requirements of small bubbled fluidized bed boilers.

Combustion in dense phase of the fluidized bed is usually incomplete. Heat released into the bed as a result of combustion can be expressed as follows:

$$\dot{Q}_b = \dot{m}_f x_b Q_c \,. \tag{1}$$

Fuel which is feed into the bed is characterized by a certain humidity hence enthalpy flux is given by the equation:

$$\dot{H}_f = \dot{m}_f \left(c_f \theta_0 + X_m H_0 \right) \,. \tag{2}$$

Energy from the bed is relayed through the heat fluxes:

- to water that flows inside the water jacket of the boiler: $\dot{Q}_w$,
- ash: $\dot{Q}_a$,
- flue gas and dust: $\dot{Q}_g$,
- radiation: $\dot{Q}_r$.

The heat flux transferred to the water flowing in the water jacket with an average temperature of the water-wall surface θ_w can be expressed by the equation:

$$\dot{Q}_w = \alpha_b A_b \left(\theta_b - \theta_w\right) \ . \tag{3}$$

The area of heat exchange between the fluidized bed and the water jacket depends on the bed height. The fluidized bed height is affected by several factors, however properties and flowrate of feeding fuel as well as primary air flowrate are critical. Heat transfer coefficient α_b takes into account both convective and radiative components of the heat transport. In the literature e.g. [1] one can find examples of empirical equations that allows to estimate value of this coefficient. Average temperature of heated surface also affect significantly the heat transfer to water. Here is of importance the effect of temperature of water returning to the boiler from the heat exchanger system. Since this variable in the present system can not be directly controlled it has to be treated as the process disturbance. Due to the continuous measurement of the water temperature at inlet to the boiler it is possible to compensate its influence on the controlled object.

Ash drained from the furnace carries the heat flux:

$$\dot{Q}_a = \dot{m}_f X_a x_d c_p \theta_b \ . \tag{4}$$

Control of ash removal consists in periodic switching on the motor of the ash remover which is controlled by measurement of the bed pressure drop thus heat flux, expressed by equation (4), can be interpreted as an average value. Control signal for the ash remover was not recorded on the test installation, so it was not included as a control input of the model.

The exhaust gases from combustion of moist fuels contain steam and dust in addition to dry gaseous components. Exhaust heat flux is thus expressed by the relation:

$$\dot{Q}_g = \dot{m}_f \left(M_g c_g \theta_b + X_m H_{\theta b} + \left(1 - x_d\right) X_a c_p \theta_b\right) \ . \tag{5}$$

The variable M_g stands for the dry mass of flue gas resulting from combustion of 1 kg of fuel. The value of this parameter depends on both the process (mainly the air excess ratio λ) and the properties of fuel burned. As previously stated, the characteristics of the fuel may vary with time, acting as disturbance to the process. The air excess ratio depends on the blower fan delivery and, within the limits allowed by the speed fluidization or additional requirements, may be subject to control.

In the transient state, the imbalance between energy fed and drained from the bed leads to changes in the bed temperature:

$$c_b m_b \frac{d\theta_b}{dt} = \dot{Q}_b + \dot{H}_f - \dot{Q}_g - \dot{Q}_r - \dot{Q}_a - \dot{Q}_w \,. \tag{6}$$

On the basis of Eqs. (1)–(6) one will notice that the bed temperature control can be carried out by changing the mass flow of fuel or primary air. Nevertheless, also the disturbance has an influence on the bed temperature. The term disturbance here refers to uncontrolled signals affecting the object output variables. These disturbances can be divided into two groups: the measurable (e.g. water temperature at inlet of the boiler) and not subjected to be measured (e.g. fuel properties). The division has a practical sense — the effect of measurable disturbances can usually be compensated in the automatic control system.

The fluidized bed height is shaped by the amount of bed material and fluidization velocity. For a fixed primary air flow the pressure drop across the bed may be the measure of its height. In practice, control of this parameter can be realized by changing the primary air flow, but mass flow of fuel and ash as well as the vacuum in the combustion chamber also influences the bed height. According to literature [1], fluctuation of fuel quality is important, immeasurable disturbance, affecting the considered parameter.

Pressure in the combustion chamber must be maintained slightly below atmospheric pressure to prevent the outflow of flue gas to the boiler-room. Changing the pressure is realized by controlling the exhaust fan speed nonetheless, mass of the exhaust gas resulting from combustion in the dense phase of the bed also has a significant impact. Therefore it can be considered that the flow rate of fuel and primary air are also control signals for the vacuum adjustment.

Heat transfer between the bed or flue gas and the water circulating in the boiler takes place through heating surfaces:

- water jacket surrounding the bed,
- water-walls of the freeboard,
- tubular heat exchangers.

The heat exchange to the water jacket of the bed takes place on relatively small area, however, due to very high heat transfer coefficient, heat flux transmitted by this route may be significant. As shown in Eq. (3), its value can be influenced by changing the temperature of the bed or its height (which determines the heat transfer surface).

In the freeboard combustible parts which, by their short residence time in the bed, had not managed to be completely oxidized are after-burning. Because of sub-atmospheric pressure in this part of the boiler there is a secondary air intake through the leaks (inspection openings, fuel feeding holes), which varies the amount of exhaust gas and its temperature. The heat flux transmitted to the water in this area, as well as in tubular heat exchangers, can be controlled by changing the temperature of flue gas or its mass flow. These factors depend directly on the bed temperature, the primary air flow and the pressure in the combustion chamber.

4 Transfer function matrix

The existence of the above-mentioned interdependencies makes it necessary to treat the fluidized bed boiler as a multivariable system. Multivariable system multiple input multiple output (MIMO) is called [5] the object of several input and output variables, where part of the inputs show the impact on more than one of the outputs.

Linear time-invariant MIMO system with m input variables, forming the vector of inputs $u(t)$, and p output variables, forming the vector of outputs $y(t)$, can be described by the input-output model in the Laplace domain in the form of the matrix $G(s)$ of size $p \times m$, for which the equation is satisfied:

$$Y(s) = G(s)U(s) \; . \tag{7}$$

This matrix is called the transfer function matrix. Matrix elements are the transfer functions $G_{ij}(s)$, representing the relationship between the j-th input and the i-th output. Vectors: $Y(s)$ and $U(s)$ are the Laplace transforms of vectors, respectively: $y(t)$ and $u(t)$ with zero initial conditions.

The water temperature at the outlet from the boiler must be controlled in supervisory system by changing the direct controllers setpoints, for the bed temperature, primary air flow, etc., according to the applied algorithm [8]. This leads to necessity of decomposing the boiler model into components associated with the level of controlled loops: the direct control level – model of the furnace $G_P(s)$, and supervisory control level – model of water heating $G_W(s)$. The Fig. 2 shows the block diagram of the decomposed model of the fluidized bed boiler.

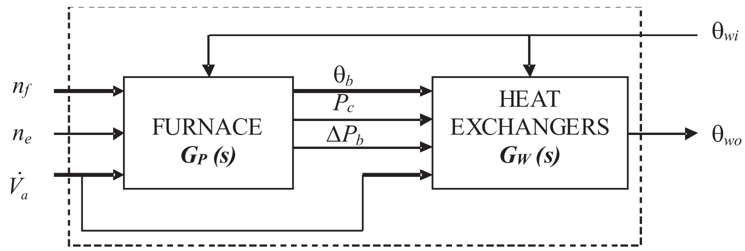

Figure 2. Block diagram of the fluidized bed boiler model.

Given the considerations outlined above, the vector of inputs (both controlled inputs and measurable disturbances) for the furnace model can be expressed as:

$$U_P(s) = \begin{bmatrix} n_f(s) & n_e(s) & \dot{V}_a(s) & \theta_{wi}(s) \end{bmatrix}^T . \tag{8}$$

Measurement mass flow of fuel that is feeding the boiler is expensive and therefore in small installations is not generally used, but taking the assumption of its proportional dependence of the drive speed of the fuel feeder it may also be considered as input for the model.

Vector of outputs for the furnace model:

$$Y_P(s) = \begin{bmatrix} \theta_b(s) & P_c(s) & \Delta P_b(s) \end{bmatrix}^T . \tag{9}$$

Vector of inputs for the water heating model:

$$U_W(s) = \begin{bmatrix} \theta_b(s) & P_c(s) & \Delta P_b(s) & \dot{V}_a(s) & \theta_{wi}(s) \end{bmatrix}^T . \tag{10}$$

Taking into account the interactions described above, the outputs independence of individual inputs can be point out by zeroing the corresponding matrix elements. This procedure will simplify the identification of the model by reducing the number of parameters to estimate. Hence, the transfer function matrix of the furnace model takes the form:

$$G_P(s) = \frac{Y_P(s)}{U_P(s)} = \begin{bmatrix} G_{P11}(s) & 0 & G_{P13}(s) & G_{P14}(s) \\ G_{P21}(s) & G_{P22}(s) & G_{P23}(s) & 0 \\ G_{P31}(s) & G_{P32}(s) & G_{P33}(s) & 0 \end{bmatrix} . \tag{11}$$

Transfer function matrix of the water heating model represents the dependence of one output signal (water temperature at the outlet from the boiler) from the five input variables. Thus, it is the multiple input single output (MISO) object:

$$G_W(s) = \frac{\theta_{wo}(s)}{U_W(s)} = \begin{bmatrix} G_{W11}(s) & \dots & G_{W15}(s) \end{bmatrix}. \tag{12}$$

5 Identification of the model

The term "identification" refers to the method of modeling the object or a process based on measurement data obtained from an experiment on the test object [7]. In industrial practice it is often the only possibility to obtain meaningful model of automated process. Due to the complicated and expensive measurement of certain variables (such as fuel mass flow) or even its inability to be measured on-line, the direct use of the energy balance model is not possible (at least for small boilers). As previously noted, the industrial processes are always exposed to disturbances. The important feature of identification methods is the ability to describe the impact of disturbances on the process. This is caused by the fact that the measurement data contain information about disturbances in addition to information on the dynamics of the process. Assuming the additive effect of immeasurable disturbances on the output of the test object, the identified structure can be represented as a block diagram (Fig. 3).

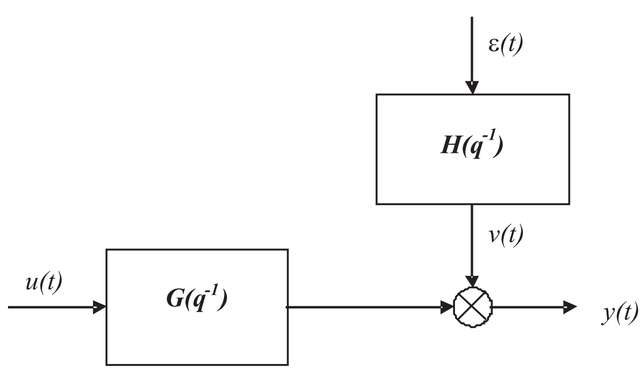

Figure 3. Block diagram of the identified ARX model.

As a result of the identification experiment the data vectors are obtained (in the form of time series): inputs $u(t)$ and outputs $y(t)$. Due to the discrete nature of the measurement data and the effectiveness of known algorithms for estimating parameters of discrete models it is convenient to replace continuous transfer functions $G_P(s)$ and $G_W(s)$ with their discrete representations in the time-shift operator q^{-1} [4]. Because the immeasurable disturbance $v(t)$ is unknown, the identification procedure assumes [7], that it is the output of a linear filter, described by the discrete transfer function $H(q^{-1})$, wherein the input signal for this filter is discrete, stationary white noise $\varepsilon(t)$. The impact of measurable disturbances is identified the same as the impact of controlled inputs. According to block diagram (Fig. 3), the equation describing the output from the process model can be given as follows:

$$y(t) = G(q^{-1})u(t) + H(q^{-1})\varepsilon(t) \ , \tag{13}$$

$G(q^{-1})$ stand for discrete form of the transfer function matrix $G_P(s)$ or $G_W(s)$ (depending on the considered component of the model).

Depending on the form of the transfer function $G(q^{-1})$ and $H(q^{-1})$ there are several types of parametric models (ARX, ARMAX, Box-Jenkins etc.). One of the most common model form in the field of control systems design is the ARX structure (autoregressive with eXogenous input). The ARX model is obtained by substituting formulas (14) and (15) into Eq. (13):

$$G(q^{-1}) = q^{-nk}\frac{B(q^{-1})}{A(q^{-1})} \ , \tag{14}$$

$$H(q^{-1}) = \frac{1}{A(q^{-1})} \ . \tag{15}$$

Equation (13) can then be written:

$$A(q^{-1})y(t) = B(q^{-1})u(t-nk) + \varepsilon(t) \ , \tag{16}$$

where $A(q^{-1})$ and $B(q^{-1})$ are matrix polynomials of the form:

$$\begin{array}{l} A(q^{-1}) = I + A_1q^{-1} + A_2q^{-2} + ... + A_{na}q^{-na} \\ B(q^{-1}) = B_1q^{-1} + B_2q^{-2} + ... + B_{nb}q^{-nb} \end{array} \ . \tag{17}$$

Matrices: $A_1, \ ... \ , A_{na}$ and $B_1, \ ... \ , B_{nb}$ are estimated matrices of ARX model parameters, nk is the discrete delay and I is the identity matrix.

Estimation of model parameters can be performed using selected algorithm. The most often used algorithm, which has a very wide application in the system identification for the purpose of automatic control, is the prediction error method (PEM) [3]. The implementation of this algorithm can be found in the software package Matlab System Identification Toolbox [4]. This software provides the comprehensive computing environment including tools and libraries useful in tasks of identification processes.

In order to illustrate the results that are potential to be achieved, the example results of identification of the model of the fluidized bed boiler with a capacity of 2 MW was presented below. It is a low-temperature water fluidized bed boiler which is working since 2007 for the district heating plant for the housing estate in the town of Goldap.

From the data, recorded during the identification experiment, two subsets with a length of 5000 s were selected. The first set of data was used to estimate the model parameters while the second one for its verification. Furnace model calculations were performed after the separation of components of this model for MISO parts. That means that the reaction was studied separately for each output for all the inputs defined in Eq. (8). It is also possible to estimate a complete MIMO model but when estimating the degrees of the matrix polynomials the used approach has proved to be more convenient. The matrix polynomials degrees *na* and *nb* as well as the delay *nk*, accepted when estimating the parameters, are compiled in Tab. 1.

It should be noted that the assumed values of [*na, nb, nk*] have been chosen by the "trial-and-error" method. A more correct approach, planned as an extension of the research presented in this paper, is to find the optimized structure of the model, taking into account the quality of obtained fit in relation to the cost of required calculations (e.g. using Akaike information criterion [7]). The graphs (Figs. 4–7) show the comparison of the measured output data (verification data subset) and simulated output using the model.

Table 1. Degrees of polynomial matrix of the identified ARX model.

Model	Output	na	nb	nk
$G_P(q^{-1})$	θ_b	[4]	[4 4 4]	[0 0 0]
	P_c	[6]	[6 6 6]	[0 1 0]
	ΔP_b	[10]	[10 10 10]	[1 1 1]
$G_W(q^{-1})$	θ_{wi}	[2]	[8 8 8 8 8]	[0 0 0 0 0]

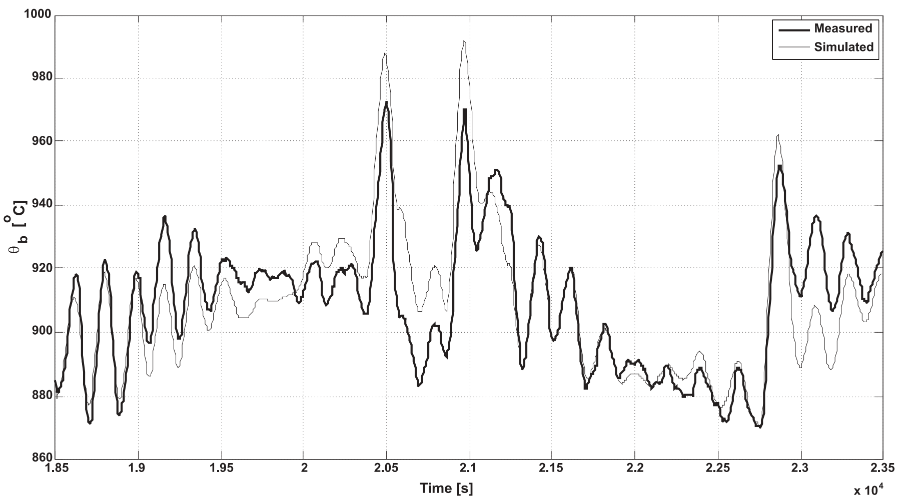

Figure 4. Comparison of measured and simulated output (bed temperature).

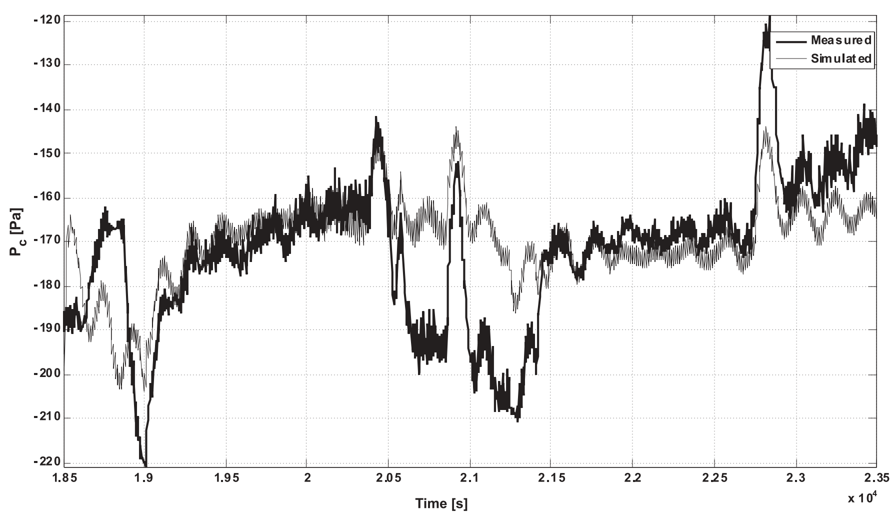

Figure 5. Comparison of measured and simulated output (pressure in combustion chamber).

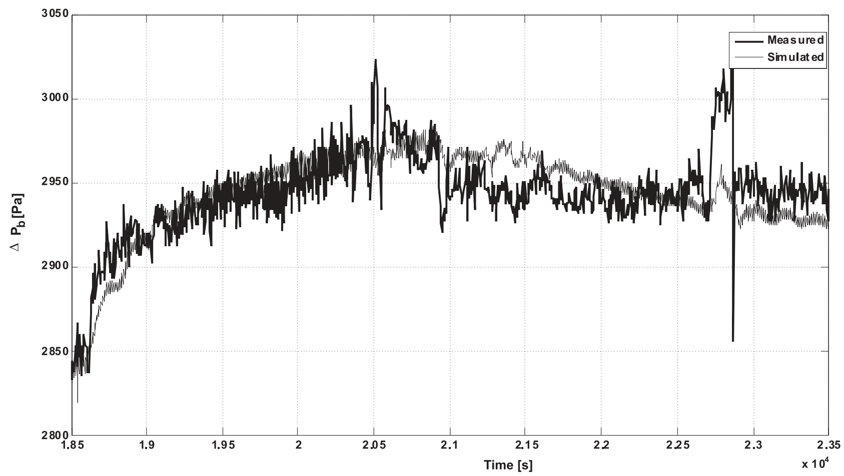

Figure 6. Comparison of measured and simulated output (pressure drop across the bed).

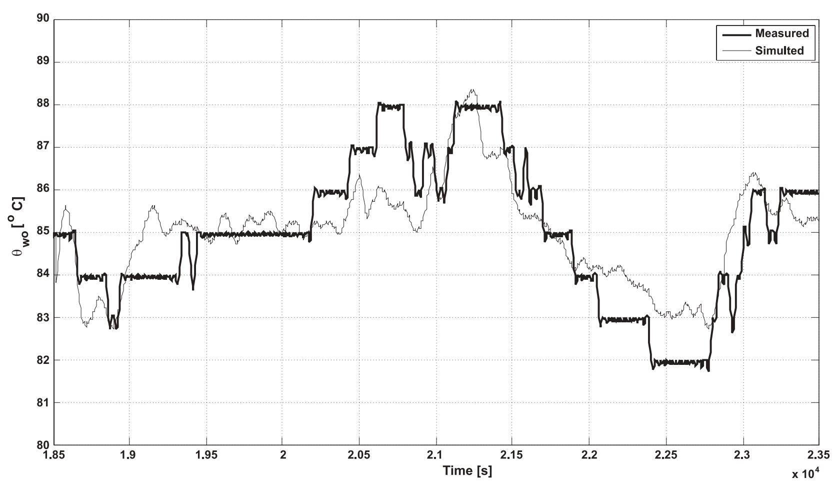

Figure 7. Comparison of measured and simulated output (water temperature).

6 Conclusions

The introduced model, due to the adopted form – transfer function matrix, is a linear model, which is the major simplification of the real, non-linear process. Nevertheless, it is necessary to emphasize that, during the identification procedure, that is carried out in real conditions of the process, the parameters estimation lead to obtain of the model, linearized around the operating point of the boiler. According to the results of sample identification the accuracy of predicted outputs is usually satisfactory. It can be noted that the adopted form of the model (ARX), although it allows the prediction of the trend, not very accurately reproduces the extreme values. Probably, a better fit would be possible to achieve by using more complex model parameterization (ARMAX, Box-Jenkins), but it would increase the computational complexity. Both the structure of the identified model and the degrees of the matrix polynomials should be determined by optimization. This issue will be the direction for further research.

Due to the empirical origin of the identified model, its quality will be determined by the designated way to perform the identification experiment. The crucial condition which has to be satisfied to obtain the model by its identification is to provide the input signals with properties that is so-called "lasting excitability". It is therefore necessary to introduce during the experiment, the additional changes in the control signals, with the amplitudes chosen so that this requirement was met, and yet did not lead to risk for operational continuity of the boiler. Serious problems may also be related with the presence of feedback that is introduced by automatic controllers. Identifiablity aspects of the presented model should be subjected to careful analysis before applying it in the controller for the industrial boiler.

The important advantage of the presented model is the possibility of its (or its MISO components) application in the controllers structure for the selected process variables. In the case of on-line identification using recursive algorithms it is also possible to apply this model in adaptive controllers that are characterized by the ability to automatically adjust the parameters of the control system to changing characteristics of the process and its surroundings. Thoroughly validated model can also be used for the process diagnostic.

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