computing@computingonline.net
www.computingonline.net

Print ISSN 1727-6209
On-line ISSN 2312-5381
International Journal of Computing

STEAM BOILER CONTROL SYSTEM USING TENSOR ANALYSIS METHODS

Viktor Sidletskyi

Department of Integrated Automated Control Systems,
National University of Food Technology, Kyiv, Ukraine, vmsidletskiy@gmail.com

Paper history:
Received 22 January 2019
Received in revised form 5 April 2019
Accepted 20 June 2019
Available online 30 June 2019

Keywords:
control system;
orthogonal basis;
tensor;
steam boiler.

Abstract: Approaches to the control of steam boilers are analyzed in the article. It is recommended to use the method of tensor analysis for identification of the current state of the heat-energy process for conducting regulating action. It is suggested that the vectors of the input and output variables of the technological process with a tensor are to be connected, which for orthonormal systems adopts a diagonal form that facilitates the calculation of regulating actions. This article presents the results of simulation when traditional methods of calculating the coefficients of the regulator are used and the calculation of the regulating action using a tensor model. The use of such a technique allows conducting the necessary regulating actions taking into account the operation of the individual apparatus. So, its operation is coordinated as a structural unit in the technological line in case of occurrence of deviations and transients.

Copyright © Research Institute for Intelligent Computer Systems, 2019.
All rights reserved.

1. INTRODUCTION

In modern heat power engineering, which is characterized by continuous growth of power facilities of plants and intensification of processes by increasing heat loads, increase of pressure and temperature of steam, etc., the dominant role is played by automatic control of processes, including automatic regulation. The complexity of processes in boiler plants requires the separation of thermal circuit into separate sections in the process of solving automation issues. Automation issues for these sections shall be solved independently, although they are interconnected. These sections are automated according to their processes and characteristics [1]. At the same time, they should be considered as a whole system with significant internal connections. At present, control systems, the regulators of which are calculated according to mathematical models, are used. When using mathematical models, a problem arises because of the impossibility of taking into account all the parameters. Mathematical models can be simplified by the rejection of some relationships between parameters. This leads to a decrease in its sufficiency. That is why, in this study we consider approaches to using tensor analysis techniques for a control system. The benefits of this approach will be the universality of the method, the ability to process and store a significant amount of information, aggregate information by allocating spaces and subspaces. That will allow interacting of all technological sites with each other. This approach to control will improve the efficiency of both one apparatus (technological site) and the whole enterprise. Implementation of such a control system is possible only due to the use of a methodology that will coordinate the work of all elements of the complex. The use of such a technique will allow conducting the necessary regulating actions taking into account the operation of the individual apparatus to coordinate its operation as a structural unit in the technological line, in case of occurrence of deviations and transients.

2. RELATED WORK

The actuality of the problem of increasing the efficiency of industrial thermal power plants and heat supply systems of industrial enterprises is given in [2, 3]. Ways of achieving the economic efficiency by means of the use of additional aggregates are shown. These are namely the use of the thermal scheme for the industrial CHPP (central heating and power plant) due to the use of reductional turbines with the production side stream for steam-converting (or evaporator) plants and for covering of the heating load. In study [4], the technological site is supplemented with the system of condensate distribution. An additional controller for controlling fuel consumption and the flow rate and level in the deaerator is installed. In [5], another important task for technological complex of production and steam consumption is revealed, that is, the compensation of peak loads, which is solved by adding another steam boiler, which performs functions of compensation of peak load, to the thermal circuit. In [6], the ways for achieving the efficiency of the complex due to the choice of one of the three options for the operation of technological equipment are highlighted. These approaches can only be implemented at the stage of development of a new technological complex or modernization of the existing one. The use of the mentioned approaches does not take into account the behavior of the complex during transient processes. For example, when the thermal load of steam boilers changes (changing the consumption of heat brings a disturbing factor to the operation of the boiler, there are transient processes that cause additional fuel consumption). It is preferable to use automated control systems for achieving economic performance. For example, in [7], technical and economic indicators are achieved by optimizing the use of metamodeling. The metamodel is used as an analytical and explanatory tool for interpreting the relationship between production costs and profits from sales of heat and electricity. In [8], it is assumed that optimal operating conditions will be achieved by adjusting the temperature in steam boilers by using the predictive model with the help of Simulink and MATLAB software packages. In [9], the program algorithm for stabilization and optimal control of boilers with the use of calculations and determination of optimal load values for each boiler included in operation is given. All the calculations were made with the help of mathematical models. In study [10], an artificial neural network model is used for predicting electricity consumption for further optimal loading of steam boilers. Artificial neural networks and adaptive systems of neuron-inaccurate output are used for creation of forecasting process models in the system of optimal control of steam boilers at a thermal power plant. Such an approach has increased the efficiency of the electrical efficiency of the CHPP by 3% [11].

Despite the considerable number of studies, outstanding issues that are related to the necessity of constant recalculation of the coefficients of mathematical models remained unsolved. Objective factors that are associated with a change in the conduct of the technological process may be the reason for this [1], as well as changes in the characteristics of the operation of the technological equipment. In principle, such an approach (training of the system in time series) cannot be used; for example, during transition processes, at the moments of running the equipment and its stops, the conditions of work of adjacent sections change [12]. This, in turn, leads to prolonged transition processes, which increase consumption of energy and material resources. Therefore, this study requires further updating.

The given task can be attributed to the task of creation of a regulating signal for achieving an effective technological regime within the current functioning of the technological complex. This can be done with restrictions to the transition process, during which the change in technological parameters will not exceed the regulated values, that is, the achievement of the given mode taking into account the current process. Ways of solution to this type of tasks were studied in [13]. But the main problem remains unsolved. It is the allocation of universal mathematical models of the entire technological complex, the coefficients of which will be converted according to the current state and mathematical model (the coefficients of which can be calculated according to the given (ideal) values of technological parameters). In this case, the regulating act can be calculated iteratively, according to the model of the current state and the model with the given technological indicators that will improve the efficiency of the entire technological complex [14]. It is necessary to calculate the controlling act for achievement of the indicators of the upper levels (efficiency of the enterprise), taking into account the indicators of the lower levels (regulated values of technological parameters), for example, increase in the efficiency of the enterprise (reducing the cost of production) by reducing the consumption of energy resources (natural gas) while not changing performance (steam costs) and performance indicators of adjacent sections, that is, generating electricity by the boiler and evaporating at the evaporation station in order to achieve a reduction in energy costs leaving the regulated performance indicators of the technological sites where the change in flow, pressure and temperature of the steam will be disturbing factors.

The use of methods of tensor analysis is the solution to these problems. For example, the following approach is suggested: the use of tensor factorization methods during the training of neural networks, which is given in the study [15, 16].

Recently methods of tensor analysis have been widely used for solving various problems. The use of tensors in control systems is a promising direction; tensors in recent years have been used in many areas, for example, the use of tensors for image processing and computer vision [17, 18]. At present, tensor methods are being already used in electrodynamics, in mechanics, in the theory of gravitational field, in the physics of elementary particles, in the study of the properties of crystals and in differential geometry [19, 20]. In [21], methods of tensor analysis were used during the process of development of a robust regulator, which is used in aircraft for reducing the shock vibration caused by the interaction of tires and runway.

Such a widespread use of tensor methods in solving modern problems in the processes of analysis and synthesis of systems can be explained by their versatility and flexibility. This is due to the fact that the tensors do not change during the transition from one coordinate system to another, allow to aggregate tasks, as well as perform decomposition of tasks, by moving from space to subspace and vice versa.

But it should be taken into account that modern control systems, including the evaporator plant control system, are built according to international (ISA-95) and European standards (IEC 62264) [22]. Control systems have a hierarchical structure, in which the lower level is the automated control system of the technological process and the highest level is presented by a business process management system.

The problem was not considered on the basis of the analysis in such an aspect. Analysis of the related works shows that it is impossible to predict all the disturbing factors that influence the operation of the steam boiler. The absence of a single universal mathematical apparatus leads to the use of different approaches in management (the introduction of additional boiler units to reduce peak loads [6], the development of predictive models [9, 10], and the use of artificial neural networks [11]). It is also not provided that modern control systems are multi-hierarchical, for which the change of the task at one of the upper levels is a disturbing factor for processes at the lower level [22]. That is why, when constructing a control system, it is necessary to take into account not only the given disturbance factors, but also the developed models of a separate area (of the steam boiler) should be integrated into a single complex with consumers. It is possible only with the use of a single methodology in modeling, that is, using methods of tensor analysis.

The problem was not considered on the basis of the analysis in this formulation. That is, it is necessary to develop a calculation procedure and the principles of using tensor models in the control system of a steam boiler with the possibility of integration of the developed methodology into a modern control system.

3. STATEMENT OF THE PROBLEM

Since the steam boiler is a rather complicated object for modeling due to the interrelation of parameters, then its scheme is conventionally simplified to three parts of the furnace, drum and superheater, for which the associated variables are isolated [1]. Simplified parametric scheme is presented in Fig. 1.

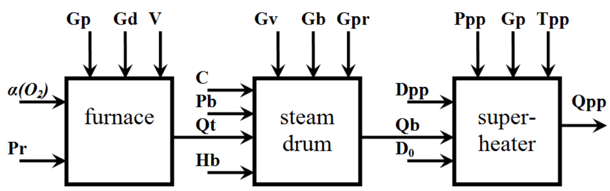

Figure 1 – Simplified parametric model of steam boiler

Fig. 1. shows: $\alpha(O_2)$ – coefficient of excess air, *Pr* – pressure depression in the top part of the furnace, *Qt* – the amount of heat released from the furnace, *Qb* – the amount of heat released from the steam drum, *Qpp* – the amount of heat released from the superheater, *V* – gas consumption, kg/s, *Gp* – fan performance (air consumption), *Gd* – performance of the smoke exhaust (flow of stack gases on the steam boiler), *Gv* – consumption of feeding water, *Gb* – steam consumption, *Gpr* – consumption of purging water, *C* – salinity of boiler water, *Hb* – level in the steam drum, *Pb* – pressure in the steam drum, *Do* – consumption of water for steam cooling, *Dpp* – boiler steam output (consumption of superheated steam), *Ppp* – pressure of superheated steam, *Tpp* –temperature of superheated steam.

For a furnace of a boiler the disturbing actions can be the change of fuel consumption *B*, change of fan efficiency *Fn* or smoke exhausts *Fg*. The regulated parameters are the dilution in the top part of the furnace *Pt* and the excess air ratio *α* or the content of free oxygen O_2 in stack gases.

The steam generating unit control can be carried out by means of dispatch. The operational data on the production of the change in the consumption of steam and the current electric power consumed can be sent to the controller or the operator, who in turn makes a decision about the change of power according to the process flow diagram. The effect on the power of steam generating unit can be made by changing the tasks to the regulators of the automatic control system, which controls the change in the flow of water, gas and air to the boiler, according to the regime load. During this the initial consumption of steam changes and, as a result, the electric power produced by the turbine generator.

Peak loads during the steam bleeding are dynamic and may be different at different times (depending on different factors of production). The steam generating unit at the same time operates at a given power.

Therefore, combining all factors that affect the output of the steam generating unit and fuel consumption, we can conclude that existing systems and approaches to boiler-house automation do not allow us to influence capacity according to the current needs of consumers.

That is why, there is a problem when technological parameters can be managed separately for their effective stabilization. And at the same time there is another task for managing all the parameters simultaneously for the efficient operation of the steam generating unit.

4. METHOD OF SOLUTION

4.1 COORDINATED APPROACH TO BUILDING A CONTROL SYSTEM

We assume that in the system of control of the heat-energy complex of the enterprise it is possible to allocate the vectors of input and output values obtained from the sensors of the technological process (measured and control signals given in the Table 1) for input parameters, that is, as a vector of parameters at the input $\vec{x}$ of the system $(x_1, x_2,\ldots, x_n)^T$ so a vector of values $\vec{y}$, which describes the passage of the technological process $(y_1, y_2,\ldots, y_n)^T$. Therefore, during the first stage, the connection $\vec{x}$ and $\vec{y}$ was introduced as a system of linear equations, which in turn allowed us to receive a quadratic form of dependence:

$$y = f(X) = \sum_{1\le j,k\le n} a_{ij}x_j x_k = X^T AX, \qquad (1)$$

where $a_{ij} \in A$ is a symmetric matrix, the elements of which are calculated according to the formula:

$$a_{ij} = \begin{cases} a_{ij} & i = j \\ \frac{1}{2}\left(a_{ij} + a_{ji}\right) & i \neq j \end{cases}, \qquad (2)$$

The columns of the matrix A represent the components of the vectors for each parameter. In this case, the deviation in the system can be calculated as

$$\Delta y = A\Delta x, \qquad (3)$$

where A is the operator of a linear equation. Then, the expression, taking into account the deviations, will look like

$$y + \Delta y = Ax + A\Delta x, \text{ or } y = Ax + Bu. \qquad (4)$$

Decomposition by the singular value SVD can be used for the transformation matrix. In the latter case, the matrix A is decomposed into a product of three matrices

$$A = U\tilde{A}V^T, \qquad (5)$$

here U is a matrix formed by orthonormal own vectors u_r of matrix AA^T, with the corresponding value of λ_r. V – is a matrix formed by orthonormal own vectors v_r of matrix A^TA. The tilde sign (~) indicates how transformation is represented by the matrix and vectors in a new basis;

$$AA^T u_r = \lambda_r u_r, \qquad (6)$$

$$A^T A v_r = \lambda_r v_r, \qquad (7)$$

where A – is a diagonal matrix, elements of which are singular values equal to the square root of eigenvalues λ_r.

The relationship between state coordinates and control systems may be represented by the following equation:

$$x(t) = U^{-1}\tilde{x}(t). \qquad (8)$$

Similarly, as the coordinates of a state vector in a new basis, one can uniquely obtain its coordinates in the initial basis; it is possible to restore the matrix according to the matrix A:

$$A = U^{-1}\tilde{A}U, \qquad (9)$$

$$\begin{aligned} \frac{dx}{dt} &= UA(t)U^{-1}\tilde{x}(t) + UB(t)u(t) \\ y(t) &= C(t)U^{-1}\tilde{x}(t) + D(t)u(t) \\ \tilde{x}(t_0) &= \tilde{x}_0 = Ux_0, \end{aligned} \qquad (10)$$

The listed matrices for the control system in the state space allow them to be used to find the optimal regulator. In order to calculate optimal control settings, the procedure lqr of the MATLAB software package, which implements the design of a linear quadratic optimal controller for continuous time systems, can be used. In case of approach to it, we receive:

$$[k,p,e] = lqr(A,B,Q,R,N), \tag{11}$$

where k is the optimal gain, p is the stationary solution and e contains the eigenvalues for the closed-loop system, in which the matrices Q and R are calculated according to expressions

$$Q = C^T * C, \tag{12}$$

$$R = B^T * B, \tag{13}$$

It calculates the optimal static matrix link in such a way that it can be used in the negative feedback circuit in the state of space. This approach was used only for comparing the operation of the regulators.

4.2 THE USE OF TENSOR ANALYSIS FOR BUILDING CONTROL SYSTEMS

Eigenvectors form an orthogonal coordinate system. In the orthogonal coordinate system for the basis vectors, the following equations should be fulfilled:

$$u_s \cdot v_k = g_{sk} = \begin{cases} 0 & for \quad s \neq k; \\ H_s^2 & for \quad s = k, \end{cases}, \tag{14}$$

where $H_s^2 = g_{ss}$ are components of the metric tensor. Accordingly, one can distinguish matrices of covariant and contravariant components of the metric tensor $\|g_{sk}\|$ and $\|g^{sk}\|$ that are diagonal:

$$\|g_{sk}\| = \mathrm{diag}\left(H_1^2, H_2^2, H_3^2\right);$$
$$\|g^{sk}\| = \mathrm{diag}\left(\frac{1}{H_1^2}, \frac{1}{H_2^2}, \frac{1}{H_3^2}\right);, \tag{15}$$

The use of tensors for connection between the basis vectors and the orthonormal basis has the following form:

$$u^s = g^{sk} v_k = \frac{u_s}{H_{(s)}^2};$$
$$u_s = H_{(s)} \vec{e}_s; \quad u^s = \frac{\vec{e}_s}{H_{(s)}}; . \tag{16}$$

The tensor, which is calculated for single orthogonal vectors, is a projector [23]. Then deviation of the vector of measured values from the given values can be calculated as a projection of the vector y on a plane, which is constructed on the control vectors and the vector of the given values.

$$\Delta y = \left(g1_{sk} + g2_{sk}\right) \cdot y, \tag{17}$$

where Δy is a calculated deviation, $g1_{sk}$ is a tensor, which is calculated for a single orthogonal vector of given values, $g2_{sk}$ is a tensor, which is calculated for a single orthogonal vector of control values (14), y is a tensor, which is calculated for a single orthogonal vector of measured values (1).

5. RESULTS

For the steam boiler DKVR 10/13 the following parameters are given in the Table 1. These parameters describe the operation of the steam boiler in terms of the quantity and quality of the generated steam. They are shown in a parametric scheme in Fig. 1, and their nominal values are given in Table 1.

Table 1. Parameters of steam boiler

Variables	Unit	Abbr.	Value
Vector *x*			
Coefficient of excess air	-	$X\alpha(O_2)$	1,4
Rarefaction in the upper part of the firebox	kPa	XPт	2,0
Amount of heat released from the furnace	MJ/kg	XQt	24,0
Amount of heat released from the drum	MJ/kg	XQb	14,0
Amount of heat released from the superheater	MJ/kg	XQss	1,0
Pressure in the steam drum	MPa	X-Ps	1.3
Consumption of nutritious water	kg/s	X -Gв	10,0
Vector *u*			
Gas flow	kg/s	U-B	0,6
Fan performance (air flow)	kg/s	U-Gp	8,7
Flow of flue gases	kg/s	U-Gg	12,5
Level in the drum	mm	U-Hd	10,3
Vector *y*			
Boiler steam output (overheated steam consumption)	kg/s	Y-Dss	10,0
Temperature of superheated steam	°C*10	Y-tss	19,4
Pressure of superheated steam	MPa/10	Y-Pss	13,0

According to Table 1: vector of output values of technological parameters $y=\{10.0,\ 19.4,\ 13.0\}$, vector of the manufacturing process of steam production $x=\{1.4,\ 2.0,\ 24.0,\ 14.0,\ 1.0,\ 1.3,\ 10.0\}$, control vector $u=\{0.6,\ 8.7,\ 12.5,\ 10.3\}$. For the given vectors the expressions (1) and (2) are used; calculated tensors of the second rank in the form of matrices of the state space system.

The matrices Q and R were calculated according to the expressions (12) and (13) for calculating the optimal regulator according to the matrices A, B, C. And the optimal regulator was calculated according to (11) means of MATLAB with the following values of matrices k and p.

Fig. 2 shows the Simulink model of a steam boiler with a LQR regulator.

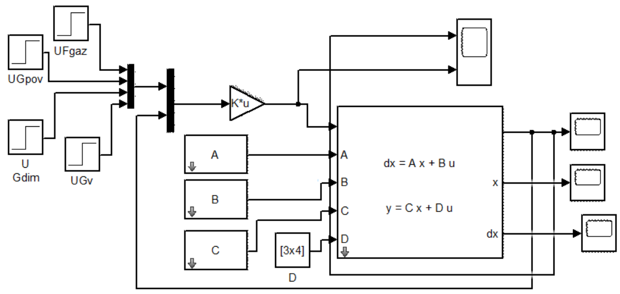

Figure 2 – Simulink of a steam boiler with a LQR regulator

Fig. 3 shows diagrams of transition processes for a steam boiler model with a LQR regulator.

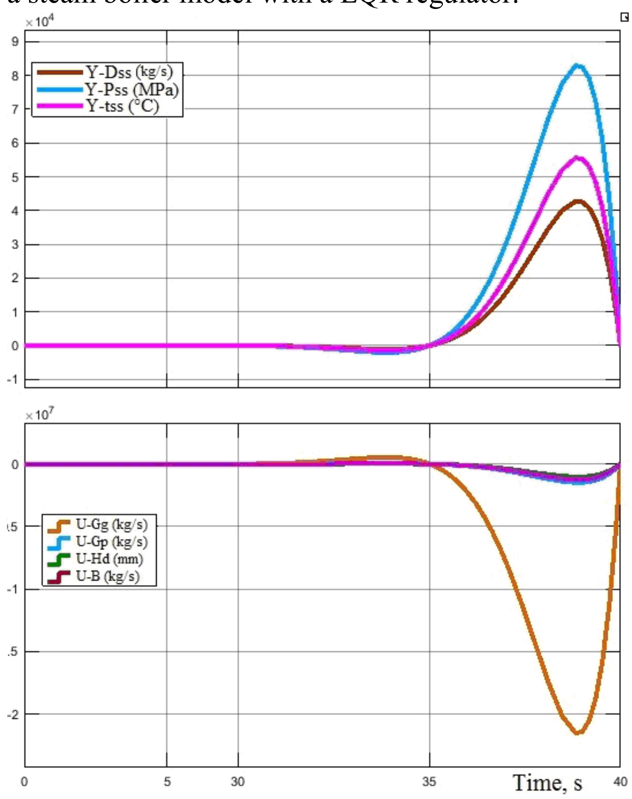

Figure 3 – Transition processes for a steam boiler model with a LQR regulator, system feedback, and control signals

According to Figure 3, the work of the regulator does not lead to the desired consequences but leads to a discrepancy between the processes. So, after 30 seconds, one can observe that all output parameters are characterized by increasing oscillations. The investigated system with the regulator is not stable.

In orthonormal coordinate system, the basis vector for variables, which describes the state of the system, will take the following form

$$r=\begin{vmatrix} -0{,}0302 & -0{,}0249 & 0{,}0054 & -0{,}0155 & -0{,}2151 & -0{,}9578 & -0{,}1858 \\ -0{,}0433 & -0{,}0358 & 0{,}0079 & -0{,}0225 & -0{,}9670 & 0{,}2350 & -0{,}0778 \\ -0{,}8494 & 0{,}5217 & -0{,}0422 & 0{,}0638 & 0{,}0193 & 0{,}0086 & -0{,}0047 \\ -0{,}3484 & -0{,}6463 & -0{,}6451 & 0{,}2081 & 0{,}0337 & 0{,}0148 & -0{,}0081 \\ -0{,}0216 & -0{,}0177 & 0{,}0039 & -0{,}0110 & -0{,}1163 & -0{,}1625 & 0{,}9794 \\ -0{,}3168 & -0{,}4912 & 0{,}7580 & 0{,}2867 & 0{,}0364 & 0{,}0159 & -0{,}0087 \\ -0{,}2315 & -0{,}2580 & 0{,}0859 & -0{,}9325 & 0{,}0483 & 0{,}0209 & -0{,}0113 \end{vmatrix}$$

Tensor g_{sk}, which is calculated according to the basis vectors, has the following form

$$g_{sk}=\begin{vmatrix} 737{,}9128708 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 158{,}8268578 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 90{,}45939147 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 56{,}59886248 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2{,}475251184 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1{,}129493257 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0{,}557273031 \end{vmatrix}$$

The functional block of the software package MATLAB “SVD Solver” was used for calculation of regulating action.

The projection of the given values on the plane of measured values was used as a signal of disagreement. The signal of disagreement was used for compensating of the deviation from the set values.

Fig. 4 shows Simulink model of steam boiler with calculation of regulating signals with the use of tensors.

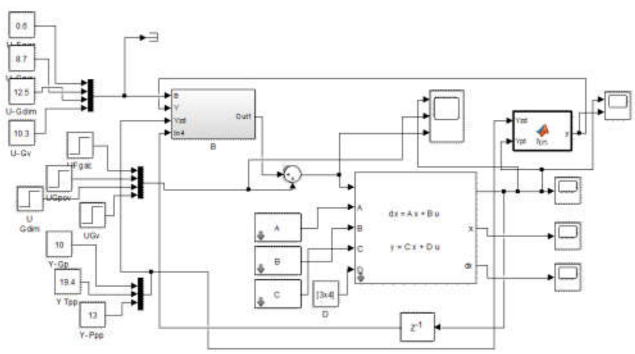

Figure 4 – Simulink model of steam boiler with calculation of regulating signals with the use of tensors

Fig. 5 shows the diagrams of transition processes for a steam boiler model including the calculation of control signals with the use of tensors.

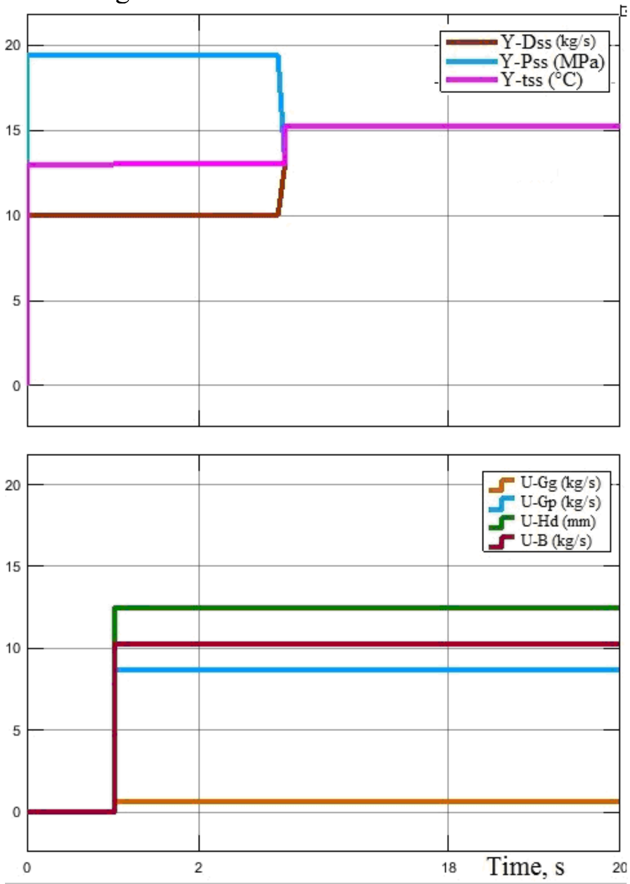

Figure 5 – Transition processes for a steam boiler model including the calculation of control signals with the use of tensors

Using a tensor model, one can observe that the system reacted to a stepped control signal and switched to a new steady state. Thus, for the same parameters and conditions a steady controlled system can be obtained when using a tensor model.

6. CONCLUSIONS

The analysis of related works proves that control of the heat and power complex is an important and urgent task. This task can be solved by modernizing technological equipment and by using more modern approaches to the control of heat and power equipment.

In this study it is recommended to use the method of tensor analysis for identifying the current state of the heat-energy process for conducting a regulating action.

For orthonormal systems, the tensor, which connects the output and input signals of the technological site, takes the diagonal form.

During the simulation process of the data given in Table 1, the regulator, which was calculated according to traditional methods, did not lead to the desired effects, but instead led to divergences in the process after 30 seconds (as it can be seen in Fig.3). At the same time, they have already reached a constant value starting from the 3-rd second after using the tensor model of the process and using the method of calculation of systems of linear equations (Fig.5).

The use of tensor analysis methods allows us to obtain a model of the steam boiler and use it in the control system. It makes it possible to further apply this approach to the operational identification of the work of the steam boiler, that is, to calculate the model based on historical and measured input and output parameters of the process.

7. REFERENCES

[1] O.I. Levchenko, V.M. Sidletskyi, *Fundamentals of Heat and Power Processes and Installations Automation, Teaching: Manual*, National University of Food Technologies, Kyiv, 2014, 227 pp. ISBN 978-966-612-153-3. (in Ukrainian)

[2] F.I. Lukhtura, A.V. Pyzhikov, and O.A. Khliestova, "On some methods of increasing thermal efficiency and reliability of industrial CHPs," *Transactions of the Priazovskyi State Technical University. Section: Technical sciences*, no. 36, pp. 88–100, Sep. 2018. (in Russian)

[3] R.-P. Nikula, M. Ruusunen, and K. Leiviskä, "Data-driven framework for boiler performance monitoring," *Applied Energy*, vol. 183, pp. 1374–1388, Dec. 2016.

[4] W. Wang, L. Li, D. Long, J. Liu, D. Zeng, and C. Cui, "Improved boiler-turbine coordinated control of 1000 MW power units by introducing condensate throttling," *Journal of Process Control*, vol. 50, pp. 11–18, Feb. 2017.

[5] H. Wang, R. Lahdelma, X. Wang, W. Jiao, C. Zhu, and P. Zou, "Analysis of the location for peak heating in CHP based combined district heating systems," *Applied Thermal Engineering*, vol. 87, pp. 402–411, Aug. 2015.

[6] G. Ahmadi, D. Toghraie, and O.A. Akbari, "Technical and environmental analysis of repowering the existing CHP system in a petrochemical plant: A case study," *Energy*, vol. 159, pp. 937–949, Sep. 2018.

[7] G. Weinberger, B. Moshfegh, "Investigating influential techno-economic factors for combined heat and power production using optimization and metamodeling," *Applied Energy*, vol. 232, pp. 555–571, Dec. 2018.

[8] S.-Y. Choi, K.-Y. Yoo, J.-B. Lee, C. B. Shin, and M.-J. Park, "Mathematical modeling and control of thermal plant in the district heating system of Korea," *Applied Thermal Engineering*, vol. 30, no. 14–15, pp. 2067–2072, Oct. 2010.

[9] Y. Skakovsky, A. Babkov, and E. Mandro, "Efficiency improvement for sugar plant boiler department work based on boiler units optimal loads distribution," *Automation of Technological and Business Processes*, vol. 9, no. 3, pp. 24-33, Nov. 2017.

[10] D. Strušnik, M. Golob, and J. Avsec, "Artificial neural networking model for the prediction of high efficiency boiler steam generation and distribution," *Simulation Modelling Practice and Theory*, vol. 57, pp. 58–70, Sep. 2015.

[11] S. Seijo, I. del Campo, J. Echanobe, and J. García-Sedano, "Modeling and multi-objective optimization of a complex CHP process," *Applied Energy*, vol. 161, pp. 309–319, Jan. 2016.

[12] I.V. Elperin, O.M. Pupen, V.M. Sidletskyi, S.M. Shved, *Automation of Production Processes: Textbook*, Kyiv: Publishing House, Lyra-K, 2015, 378 p. (in Ukrainian)

[13] P. Terán, "On consistency of stationary points of stochastic optimization problems in a Banach space," *Journal of Mathematical Analysis and Applications*, vol. 363, no. 2, pp. 569–578, Mar. 2010.

[14] V.M. Sidletskyi, I.V. Elperin, V.V. Polupan, "Analysis of non-measuring parameters at the level of distributed control for the automated system, objects and complexes of the food industry," *Transactions of the National University of Food Technologies*, vol. 22, no. 3, pp. 7-15, Mar 2017. [Online]. Available: http://dspace.nuft.edu.ua/jspui/handle/123456789/24682. (in Ukrainian)

[15] A. Cichocki, R. Zdunek, A.-H Phan., S.-I. Amari, *Nonnegative Matrix and Tensor Factorizations: Applications to Exploratory Multi-way Data Analysis and Blind Source Separation*, J. Wiley & Sons, Chichester, 2009, 512 p.

[16] M.C. Renhe, M.B. Vieira, and C. Esperança, "A stable tensor-based method for controlled fluid simulations," *Applied Mathematics and Computation*, vol. 343, pp. 195–213, Feb. 2019.

[17] S. Aja-Fernández, R. de Luis García, D. Tao, X. Li (eds.), *Tensors in Image Processing and Computer Vision*, London: Springer, 2009, 470 p.

[18] L. Qi, C. Xu, and Y. Xu, "Nonnegative tensor factorization, completely positive tensors, and a hierarchical elimination algorithm," *SIAM Journal on Matrix Analysis and Applications*, vol. 35, no. 4, pp. 1227–1241, Jan. 2014.

[19] I.Y. Zubko, "Computation of elastic moduli of graphene monolayer in nonsymmetric formulation using energy-based approach," *Physical Mesomechanics*, vol. 19, no. 1, pp. 93–106, Jan. 2016.

[20] Y.-C. Hu, T.-L. Li, C.-S. Fan, D.-Y. Wang, and J.-P. Li, "Three-dimensional tensor controlled-source electromagnetic modeling based on the vector finite-element method," *Applied Geophysics*, vol. 12, no. 1, pp. 35–46, Mar. 2015.

[21] S. Kuntanapreeda, "Control of shimmy vibration in aircraft landing gears based on tensor product model transformation and twisting sliding mode algorithm," *MATEC Web of Conferences*, vol. 161, pp. 02001, 2018.

[22] V.M. Sidletskyi, I.V. Elperin, "Expansion of the functional capabilities of automated control systems of technological objects," *Scientific Journal "Engineering and Energy" (Scientific Bulletin of NUBiP of Ukraine, Series: Engineering and Power Engineering of the Agroindustrial Complex)*, no. 256, pp. 113-121, Mar 2017. [Online]. Available: http://journals.nubip.edu.ua/index.php/Tekhnica/article/view/8241. (in Ukrainian)

[23] I.Yu. Zubko, N.D. Nyashina, *Mathematical Modeling: Discrete Approaches and Numerical Methods: studies. Allowance*, Perm: Publishing House of Perm National Researches Polytechnic University, 2012, 365 p. (in Russian)

Viktor Sidletskyi*, received Ph.D. from National University of Food Technology. He is currently an Assistant Professor at Department of integrated automated control systems, National University of Food Technology.*

His areas of interest are decision support system, tensor analysis, simulation of complex systems and introduction of control systems.