EXERGY DIAGNOSIS OF COAL FIRED COMBINED HEAT AND POWER PLANT WITH APPLICATION OF NEURAL AND REGRESSION MODELLING

by

Wojciech STANEK [*] ***and Michal BUDNIK***

Institute of Thermal Technology, Silesian University of Technology, Gliwice, Poland

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Mathematical models of the processes, that proceed in energetic machines and devices, in many cases are very complicated. In such cases, the exact analytical models should be equipped with the auxiliary empirical models that describe those parameters which are difficult to model in a theoretical way. Regression or neural models identified basing on measurements are rather simple and are characterized by relatively short computation time. For this reason they can be effectively applied for simulation and optimization of steering and regulation processes, as well as, for control and thermal diagnosis of operation (e. q. power plants or combined heat and power plants). In the paper regression and neural models of thermal processes developed for systems of operation control of thermal plants are presented. Theoretical-empirical model of processes proceeding in coal fired combined heat and power plant have been applied. Simulative calculations basing on these models have been carried out. Results of simulative calculations have been used for the exergetic evaluation of considered power plant. The diagnosis procedure let to investigate the formation of exergy costs in interconnected components of the system of combined heat and power, as well as, investigate the influence of defects in operation of components on exergy losses and on the exergetic cost in other components.

Key words: *mathematical modelling, neural networks, combined heat and power plant, exergy, diagnosis*

Introduction

The thermal diagnostics [1-4] is a part of the technical diagnostics. Its aim is to identify the changes in states of the machines, devices and industrial system. Nowadays, in the field of the thermal diagnostics, there are researches on decreasing the processes' energy consumption and the process operational costs. The existing diagnostics systems have been equipped with modules which allow to indicate causes of excessive energy consumption. A combined heat and power (CHP) unit represents a complex energy system [1, 5]. It consists of many elements such as: a boiler, a turbine, regenerative heat exchangers, a condenser, heat exchanger for district water heating, and a cooling tower. These elements are all connected

* Corresponding author; e-mail: wojciech.stanek@polsl.pl

and interdependent. The set of CHP components and connections between them represent a complicated energy system. The comprehensive analysis of such complex system requires the application of the system analysis. For the purpose of determination of thermodynamic perfection of the system these tools should be supplemented with exergy and cumulative exergy analysis.

To estimate the influence of the operating parameters on energy consumption of co-generation of electricity and heat process, operating deviations of the specific heat consumption and specific energy and exergy consumption indicators are applied in the diagnostics systems. The most precise information of these deviations one can achieve using a simulator of power plant [1, 5, 6]. Energy diagnosis however useful is not sufficient and should be supplemented with the possibility of performing exergy as well as environmental investigation. The energy evaluation of energy systems with the application of neural and regression modelling has been previously published, for example, in [1, 5, 6]. In this paper the main purpose is to connect the empirical modelling (both – regression and neural) with the exergy evaluation of power and heat and power units.

Investigation of the influence of operational parameters on these losses plays a key role in searching elements of increased thermodynamic imperfection. Additionally the analysis of direct exergy effects is not sufficient. In complex energy systems due to interconnections one component indicates losses in other. To make this picture clearer let consider power plant. Every one knows that the less effective from the exergetic point of view is the boiler. But the boiler purpose is to feed the turbine. For this reason any imperfections appearing in the performance of turbine cause the increase of steam consumption. The increase in steam production in boiler is caused in this case by the imperfection of turbine. Also the additional exergy losses accompanying this increase of steam production appear in boiler but are induced by turbine. This is the reason why the cumulative exergy calculus is necessary to apply.

Thermoeconomic [2] analysis goes a step forward than exergy analysis by taking into account this fact by introducing the concept of cost. In a few words, the cost of a flow can be defined as the amount of resources needed to produce that flow. The thermoeconomic analysis [2-4, 9-12] is based on the concept of exergetic cost.

A brief description of theoretical fundamentals of exergetic cost determination and its application are presented. The applied method of calculations is based on the rules of determination of cumulative exergy consumption. The authors discussed within the paper the additional possibilities ensured by exergetic cost analysis in comparison with the direct exergy consumption analysis. Results of calculations concern one of the modern Polish power plants. Basing on the obtained results the Authors formulated several conclusions the shown the advantages of application of exergetic cost analyses.

Exergetic cost

In this section the fundamentals of calculations of exergetic cost making use of the balance of cumulative exergy is briefly explained. The balance of cumulative consumption can be applied after some modifications for calculation of following indices:

- cumulative energy consumption (energy cost) [7, 8],
- cumulative exergy consumption (exergy cost)[8, 9],
- cumulative consumption of non-renewable natural resources (thermoecological cost TEC) [7, 8] ,

– cumulative emission of CO_2 (thermo-climatic cost TCC) [13],
– proecological tax (ExTAX) [14].

The schematic diagram of system with specified productive components and their connections with considered *j*-th productive element are presented in fig.1.

The balance equation of cumulative exergy consumption (CExC) [8] is base upon the statement that the CExC of the product of element of considered system results from the CExC burdening the semi-finished products and by-products and from the exergy of natural resources extracted from nature [7, 8]. For this reason cumulative exergy is conserved and the balance equation does not directly include exergy losses. Basing on this statement Szargut proposed the general form of the cumulative exergy balance equation. In the simplified form it can be presented as:

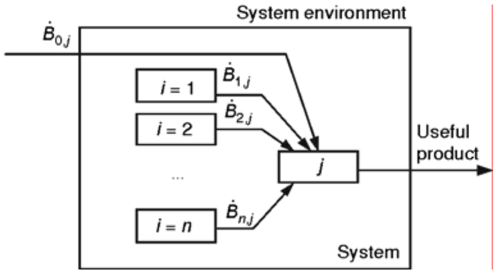

Figure 1. Connection between components of the system

$$b_j^* = \sum a_{ij} b_i^* + \varphi_{0j} \tag{1}$$

where b^*_i and b^*_j are the specific cumulative exergy consumption burdening the production of *j*-th and *i*-th element of considered system, a_{ij} is the coefficient of consumption of *i*-th resource of considered *j*-th process, and φ_{0j} – the exergy of resources delivered from environment of investigated system.

Nevertheless eq. (1) does not include the exergy loss, the results of calculation are dependent on it. The perfection of the process is included in the coefficients of specific consumption a_{ij}.

Basing on the results of calculations of cumulative exergy indices the specific exergetic cost can be evaluated. For the *j*-th useful product it can be expressed as [8, 9, 11, 12]:

$$k_j^* = \frac{B_j^*}{B_j} = \frac{b_j^*}{b_j} \tag{2}$$

where B [kW] is the exergy flow and B^* [kW] – the cumulative exergy flow.

The cost expresses the total cumulative exergy expenditures of resources required to obtain the specific exergy b_j of *j*-th useful product. The exergetic cost is higher than the specific exergy consumption loco considered process. The higher is the exergetic cost than unit the less favourable from the point of view of savings of natural resources.

In the case of large energy systems it is not convenient to use the cumulative exergy balance in form of eq. (1). In this case it is more efficient to calculate the exergetic cost basing on the incidence matrix [4, 9, 12]. The incidence matrix describes the connections between elements of the system and also between elements and environment. The number of rows of incidence matrix is equal to the number of components *n* and the number of columns of incidence matrix is equal to number of flows appearing within the boundary of analysed system *m*. The elements of incidence matrix are defined as follows:

$$a_{ij} = \begin{cases} +1 & \text{if flow "}j\text{" enter the component "}i\text{"} \\ -1 & \text{if flow "}j\text{" leaves component "}i\text{"} \\ \;\;0 & \text{if there is no connection between component flow "}j\text{" and component "}i\text{"} \end{cases}$$

Basing on the defined incidence matrix the balance equation of exergetic cost takes the following form [9]:

$$[\mathrm{A}]\cdot\vec{\mathrm{B}}^{*}=0 \tag{3}$$

where [A] is the incidence matrix and $\vec{\mathrm{B}}^{*}$ – the cumulative exergy vector.

The number of unknown values should be equal to the number of flows. Usually in practical cases the number of unknown is greater than the number of equations of type (3). We can distinguish three reasons of existence of the surplus of unknown [9]:

(1) Some flows of resources are delivered to the system from outside of balance boundary. Resources taken from extracted natural environment (for example fossil fuels) belong to this group. Each flow of resources delivered from the environment of the system introduced the surplus of unknown values of exergetic cost in the balance system described by eq. (3). In this case the surplus of unknown has to be externally assessed. If the flow is coming from the deposit of natural resources we assess the exergetic cost directly as exergy of this flow.

(2) Also some waste product are generated in the components of the system besides useful products. They represent external exergy losses. If it is not possible to use the wastes the value of their usefulness are equal to zero. In some case their exergetic value can be negative, for example when before rejection of wastes we have to clean its flow in abatement installation,

(3) There are more than one useful product in some components of the system. Each additional product introduces additional unknown value of exergetic cost into the system of balance equations. To solve these problems the method of exergetic cost can be applied. In this method we assumed [7-9, 11] that the exergy of useful product is burdened by the same exergetic cost.

It leads to the following additional equation:

$$k_{j,1}^{*}=k_{j,2}^{*}=....k_{j,n}^{*} \tag{4}$$

where n are the numbers of co-generated products in j-th component, and $k^{*}_{j,i}$ is the cumulative exergy cost of i-th product in j-th component.

The balance of cumulative exergy expressed by eq. (3) can be used for the determination of the exergetic cost of particular flow. More interesting would be the investigation of the cumulative exergy cost for particular components and moreover the effects of induced exergy. The investigation of induced exergy can be one by decomposition of exergy cost of considered component k^{*}_{j} into parts resulting from the interactions of other components. For this reason the following formula proposed by Valero can be applied:

$$k_{Pj}^{*}=1+\sum_{i=1}^{n}\varphi_{i,j} \tag{5}$$

where j denotes the considered components, n – the number of components in the considered energy system, and φ_{ij} is the coefficient expresses the irreversibility generated in i-th component of the system in order to obtain considered j-th product.

The detailed algorithm of φ_{ij} is presented in Valero's works [3, 4, 10-12].

Model of the plant

For the simulative calculation of influence of operational parameters on exergetic cost the mathematical model of the CHP plant has to be applied. A mathematical model can be achieved in two ways. Using the physical laws, an analytical model is formulated. Carrying out the measurements with the application of the identification methods, an empirical model is determined [1, 5, 6]. A development of the measuring techniques and a computer technology causes a wider application of the mathematical modelling of the processes basing on registered measurements data. The advantages of constructing models on the basis of the process identification methods prevail:

– the analytical models are impossible or extremely difficult and time-consuming to construct (for example modelling of the processes proceeding in the steam power stations), and
– real-time optimisation of the process parameters.

The models obtained on the basis of the identification of the processes have some features which differ from the analytical models:

– their application is limited (can be applied in a specific range, extrapolation is the most often inadmissible),
– they do not explain physical meaning of the process, and
– they are quite easy to elaborate and apply.

The mathematical models obtained as a result of the identification are used to:

– simulate and optimise the processes,
– regulate and control the objects, and
– diagnose the process.

A conventional CHP unit is a complex energy system. Such a system comprises a boiler, a turbine, a condenser, the regenerative heat exchangers, district heat exchanger and a cooling tower. A useful tool which identifies complex systems can be an integration of the analytical modelling techniques with the artificial intelligence techniques in a hybrid model [1]. An elaborated model of a power unit contains models of: a boiler, a steam-water cycle and a cooling tower. Figure 2 presents a diagram of the hybrid model of a CHP unit.

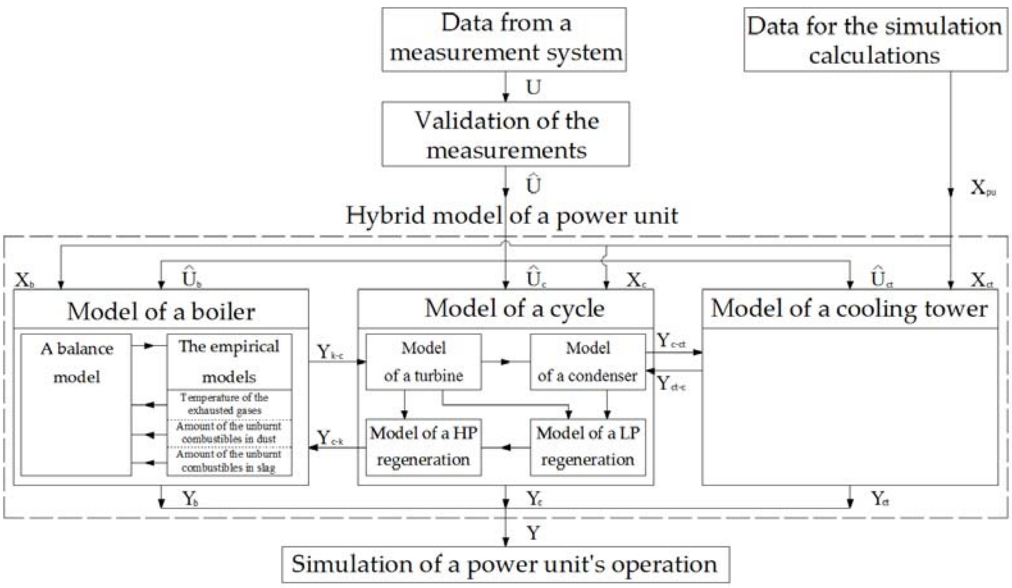

Figure 2. The diagram of the simulation hybrid model of the power unit

The developed hybrid model of the boiler includes a balance model as well as the empirical models worked out by the means of the regression and the neural techniques. The balance model has been built basing on DIN-1942 standard [15]. The neural model describes the dependence between the flue gas temperature and the main operating parameters of the boiler. The regression models are describing a dependence of a mass fraction of unburnt carbon in slag and dust on the boiler operating parameters. These models were developed by using a step-wise regression method.

A model of a steam-water cycle comprises a model of a turbine, the models of the heat exchangers and a model of a condenser [1]. A model of a turbine contains the mass and energy balances for each part of the turbine, the models of the steam expansion lines for each group of turbine's stages and the auxiliary empirical functions (identified both – basing on neural and regression methods). There are methods which use a flow modelling or methods based on the steam flow capacity and efficiency of the process equations applied for the evaluation of the steam expansion line in a turbine. Combining these methods is also possible. However, the flow computations demand knowledge of a flow system geometry. Such computations are time-consuming and require the complex models. The computations on the basis of the steam flow capacity and efficiency of the process equations are simpler and less time-consuming but require the identification of the empirical coefficients of the equations.

Results of calculations

The simulative calculations of the influence of operational parameters on exergetic cost have been carried out for the conditions of one of Polish CHP plant. Analyzed system is the CHP power unit of electric power 57 MW_e and thermal power 109 MW_t. The live steam pressure and temperature is 13 MPa and 535 ºC. Investigated steam-water cycle include the steam turbine, the condenser (CON), the high-temperature and low-temperature regeneration system, the feed water tank with deaerator (DEA) and the district heat exchanger (DH). The low-temperature and high-temperature regeneration system contains two regenerative exchangers each (LP1, LP2, HP1, HP2). The schematic diagram of the system is presented in fig. 3.

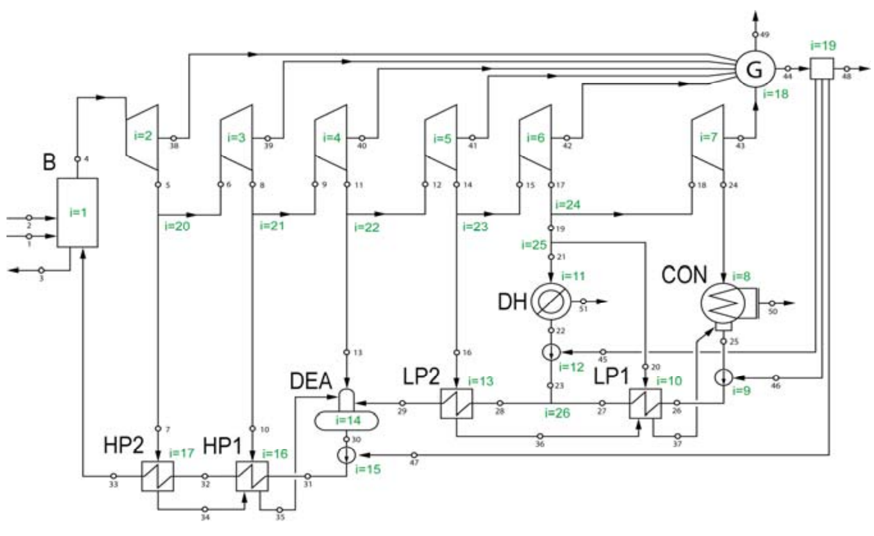

Figure 3. Schematic diagram of analyzed CHP plant

Identification of empirical models

Boiler modeling

Energy efficiency is the most common factor applied in practice to evaluate the boiler's effectiveness. It can be determined by a direct and an indirect method. Most often, in the case of big boilers fired with coal, the consumption of fuel is measured with no satisfactory accuracy, or it is not measured at all. Thus, the indirect method is recommended [15]. The indirect method of the boiler's energy efficiency determination is simplified and explained by:

$$\eta_{EB} = 100 - L_{fg} - L_{ch} - L_o \tag{6}$$

where L_{fg} is the flue gas losses, L_{ch} – the losses due to unburnt coal in slag and dust, and L_0 – the energy losses other than L_{fg} and L_{ch}.

In the case of big boilers fired with coal the flue gas losses L_{fg} and losses due to unburnt coal L_{ch} have a dominant influence on energy efficiency. These losses result from the following equations:

$$L_{fg} = \frac{n''_{ss}(Mc_p)_{ss}(t_{fg} - t_0)}{W_d} \tag{7}$$

$$L_{ch} = \frac{(g_s c_s + g_d c_d) W_{dC}}{W_d} \tag{8}$$

where n''_{ss} is a specific amount of dry flue gases, $(MC_p)_{ss}$ – the mean molar heat capacity of the flue gas. t_{fg} and t_0 are the flue gas and ambient temperature. c_d is the average mass fraction of element C in dust, c_s – the average mass fraction of element C in slag, g_s and g_d are the specific amount of slag and dust per unit of consumed fuel, W_{dC} is the lower heating value of the C element, and W_d – the lower heating value of fuel.

Basing on the knowledge of energy efficiency, the exergy efficiency of simple energy processes (*e. g.* water boiler) can be calculated as follows [7, 8]:

$$\eta_{BB} = \frac{\dot{G}_p(b_p - b_w)}{\dot{P} b_{ch}} = \eta_{EB} \frac{W_d}{b_{ch}} \left(1 - \frac{T_0}{T_m}\right) \tag{9}$$

where $\dot{G}_p$ is the mass flow rate of steam, b_p and b_w are the specific exergy of steam or hot water and specific exergy of feed water, $\dot{P}$ is the mass flow rate of fuel, b_{ch} – the specific chemical exergy of fuel, T_m – the mean thermodynamic temperature of the steam/water flux during heating-up in the boiler, and T_0 – the ambient temperature.

Mean thermodynamic temperature is defined as:

$$T_m = \frac{\Delta i}{\Delta s} \tag{10}$$

where Δi and Δs are the increase of specific enthalpy and entropy during heating up of the flux of steam in the boiler.

In the case of big steam boilers, there are often two or more fluxes of produced steam (*e. g.* live steam and reheated steam). In such cases, the simplified form of eq. (9) should be developed to the following form [7, 8]:

$$\eta_{BB} = \frac{1 - L_{fg} - L_{ch} - L_o}{a}\left(1 - T_0 \frac{\sum_i\left(\dot{G}_i \Delta s_i\right)}{\sum_i\left(\dot{G}_i \Delta i_i\right)}\right) \tag{11}$$

where $\dot{G}_i$ is the i-th flux of steam, Δs_i – the increase of entropy of i-th flux of steam, Δi_i – the increase of enthalpy of i-th reheated flux of steam, and $a = b_{ch}/W_d$ – the ratio of chemical energy to chemical exergy of fuel [7, 8].

The factor a depends on the fuel's composition. In the case of solid fuels as hard coal, coke, lignite, the factor a can be determined by [8]:

$$a = \frac{b_{ch}}{W_d} = 1.0437 + 0.1896\frac{h}{c} + 0.0617\frac{o}{c} + 0.0428\frac{n}{c} \tag{12}$$

where c, h, o, and n denote mass fraction of carbon, hydrogen, oxygen, and nitrogen element in fuel, respectively.

Basing on the knowledge of exergy efficiency of the boiler the total exergy losses can be easily calculated by means of the formula:

$$\delta \dot{B}_{BB} = 1 - \eta_{Bk} \tag{13}$$

These losses are characterized by the degree of thermodynamic imperfection of processes proceeding in the boiler.

The presented model of the boiler has been developed with the application of both the analytical modelling and the empirical modelling methods (neural and regression). Such models are classified as hybrid ones. The analytical part of the model includes balance equations compatible with the methodology of DIN 1942 standard [15]. The empirical models express the dependence of flue gas temperature and mass fraction of unburnt combustibles in solid combustion products on operational parameters of the boiler. Simplified scheme of the network taken into account in the case of flue gasses temperature model has been presented in fig. 4.

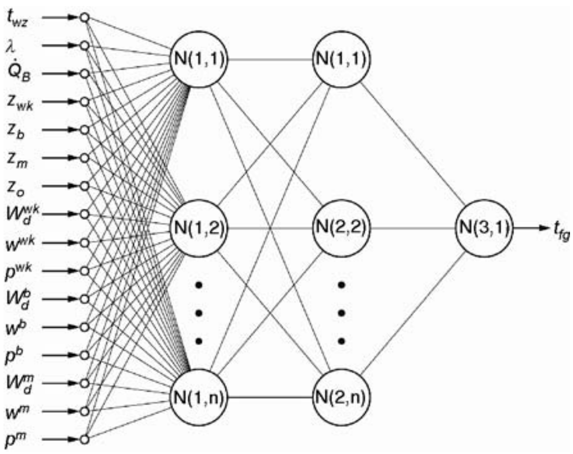

Figure 4. Structure of the neural model describing the flue gas temperature

Independent variables of the model are: feed water temperature t_{wz}, excess air ratio λ, boiler thermal power Q_B, ratio of chemical energy of coal z_{wk}, ratio of chemical energy of biomass z_b, ratio of chemical energy of sludge z_m, ratio of chemical energy of furnace oil z_o, fuel lower heating value of hard coal W_d^{wk}, fuel lower heating value of biomass W_d^b, fuel lower heating value of sludge W_d^m, mass fraction of ash and moisture in hard coal p^{wk}, w^{wk}, mass fraction of ash and moisture in biomass p^b, w^b, and mass fraction ash and moisture in sludge p^m, w^m.

Flue gas temperature t_{fg} represents the dependent variable (output) of the neural model.

The comparison of training effectiveness of the neural network presented in fig. 4 with the results obtained by means of the regression model has been presented in fig. 5.

The comparison of verification of the neural and regression model have been presented in fig. 6.

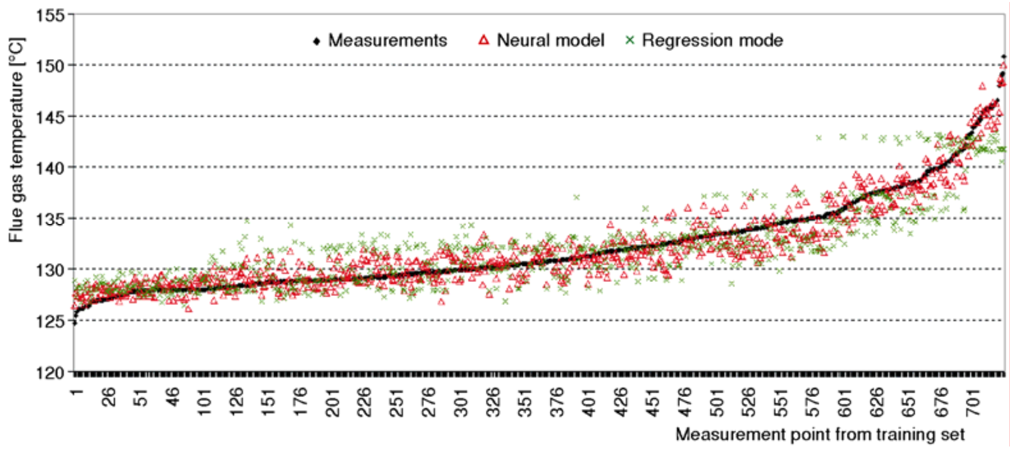

Figure 5. Comparison of the training process of the neural net with the regression model (color image see on our web site)

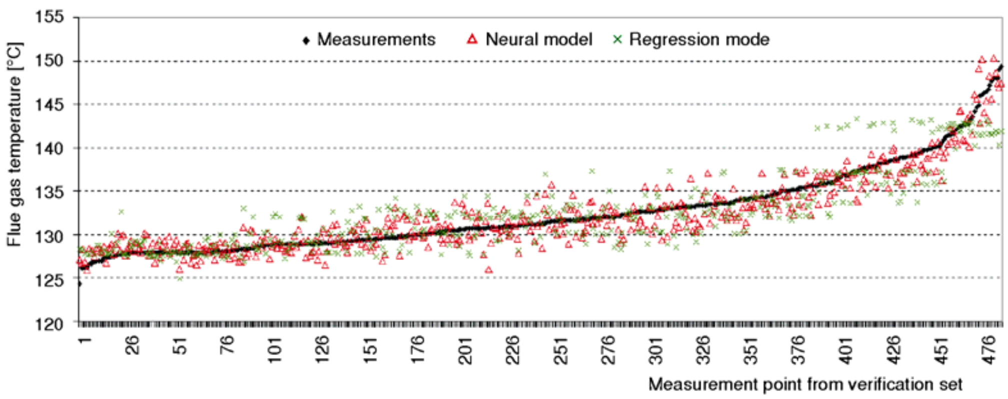

Figure 6. Comparison of the verification process of the neural net with the regression model (color image see on our web site)

In the case of both, the training set and verification set, the neural model has achieved better results.

Steam cycle modelling

In the steam cycle of turbine two groups of components require the application of auxiliary empirical models:
- turbines, and
- heat exchangers.

In the case of turbines (with the division between particular stages) in order to describe the process of steam expansion, in the practical calculations the authors identify two different kinds structure of the models. In the first kind of the model answer was the parameters as pressure and temperature of steam at the outlet of turbine. In the second kind of the model the internal efficiency has been assumed as answer.

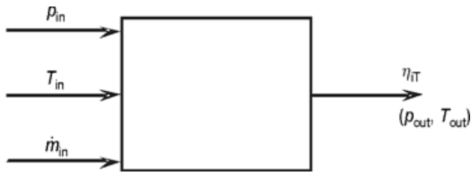

Figure 7. Simplified structure of black-box model of turbine stages

The schematic diagram of such model is presented in fig. 7.

In both of considered cases as the inputs the following parameters have been introduced:

$\dot{m}_{in}$ – flow of steam at the inlet of turbine, p_{in} – pressure of steam at the inlet of turbine, and T_{in} – temperature of steam at theinlet of turbine.

The empirical models of expansion in turbine stages have been identified both by regression and neural methods. The comparison of both method of model identification for selected case of 4th stage of turbine is presented in fig. 8 and 9.

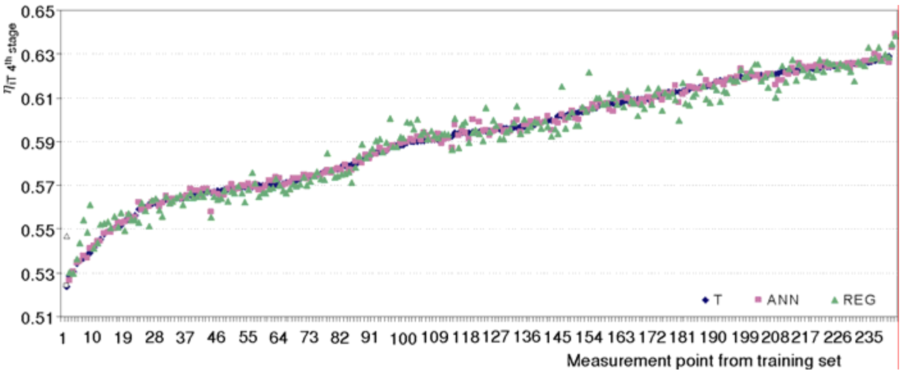

Figure 8. Comparison of the training process of models of turbine stage identified with regression and neural method (T – measurement, ANN – neural model, REG – regression model) (color image see on our web site)

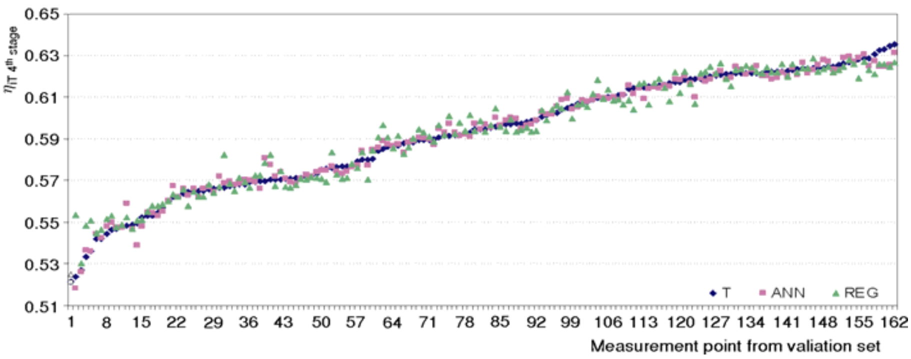

Figure 9. Comparison of the verification process of models of turbine stage identified with regression and neural method (T – measurement, ANN – neural model, REG – regression model) (color image see on our web site)

The better results have been achieved in the case of neural identification. The quality of models characterized by correlation factor is compared in tab. 1.

Table 1. Comparison of model quality

Identification method	Neural		Regression	
Correlation factor, R^2	Training	Validation	Training	Validation
– efficiency of 4th turbine stage	0.9955	0.9879	0.9636	0.9629
– flue gas temperature	0.9157	0.8916	0.7632	0.7650

Example results of exergy cost analysis

The developed plant simulator and the procedure for energetic and exergetic cost calculations can be used for the following analysis:

- influence of the operational parameters on the energy indices and their deviations between reference (x_0) and operational state (x_1),
- influence of the operational parameters on the exergy costs of particular flows between products of the system [16],
- influence of operational parameters on the immediate and inducted exergetic cost of the component operation.

The latter is presented in this section. The results of calculation of cumulative exergetic cost burdening the operation of boiler and turbine in case of reference state is presented in fig. 10.

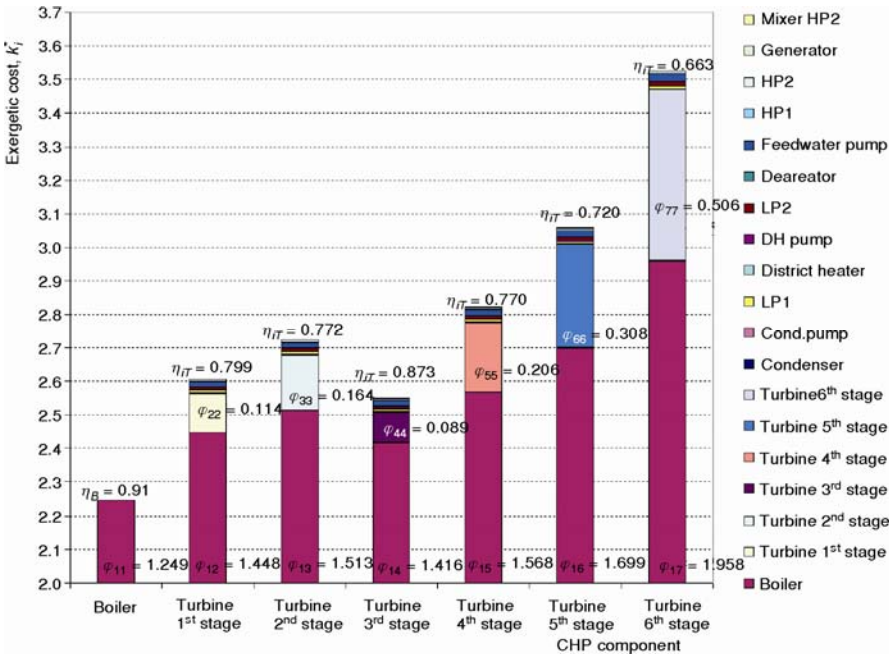

Figure 10. Cumulative exergetic cost in reference state model (color image see on our web site)

The immediate exergetic cost in the case of the boiler (component i = 1) represents the total exergetic cost. In the presented in fig. 10 example it can be observed that in the case of steam turbine two components of exergetic cost are of significant meaning: the immediate exergy cost caused by own irreversibility in the turbine and moreover the induced cost caused by the thermodynamic imperfections in the boiler. It can be noticed that the inducted cost resulting form boiler influence is greater than the own exergetic cost of turbine. The lower is the internal efficiency of turbine the higher is as well immediate cost as inducted cost. Realizing the same calculations for the other state of plant the developed algorithm let us to investigate the improvement or the increase in malfunction of the component on the cost formation in particular components of the system. For example this is presented in fig. 11 results of calculations of exergetic cost in the state with decreased of boiler efficiency whereas in fig. 12 with decreased internal efficiency of the 2nd stage of steam turbine.

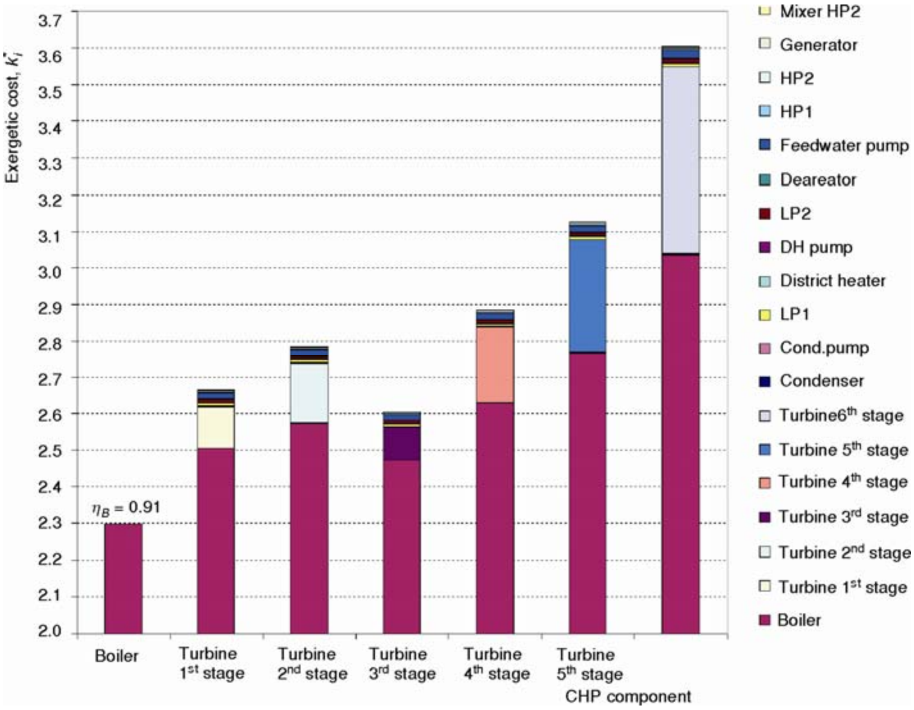

Figure 11. Cumulative exergetic cost in the state with decreased boiler efficiency (color image see on our web site)

It can be observed that the developed algorithm let us easily investigate the propagation of irreversibilities within the system. The decrease of boiler efficiency leads directly to increase of immediate exergetic cost appeared directly in boiler as well as in other components. For example induced exergy loses in turbine stages, fig. 11, and regeneration system of the CHP, fig. 13. The lower is the internal efficiency of turbine stage the stronger is the induction of irreversibilities caused by boiler, which is good illustrated on district heater, fig. 14. In the case of consideration the decrease in internal efficiency of turbine, fig. 12, we can additionally observe the propagation of exergetic losses induction between particular stages of the boiler.

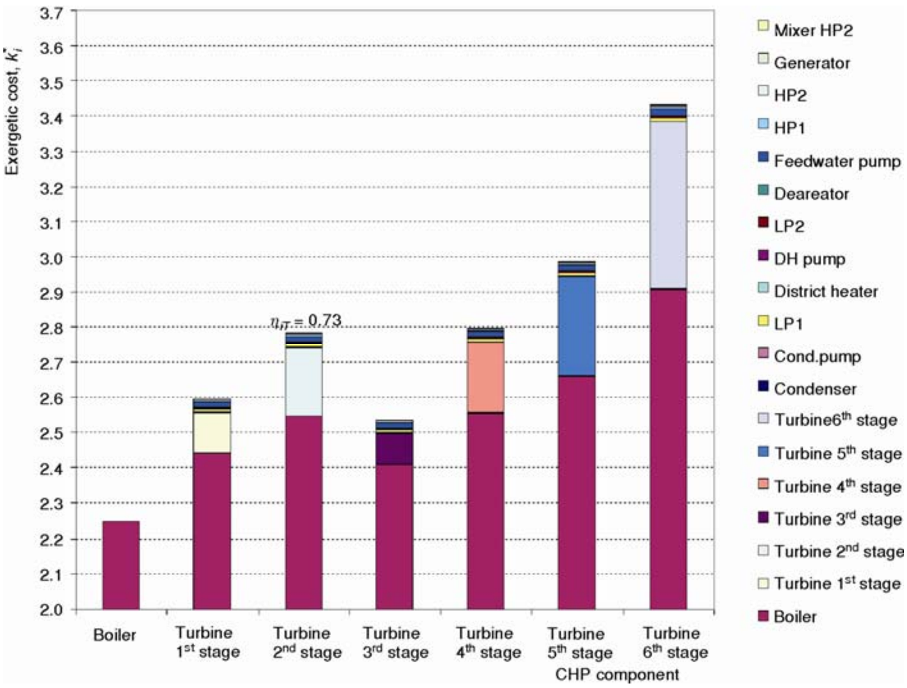

Figure 12. Cumulative exergetic cost in the state with decreased internal efficiency of 2nd stage of turbine (color image see on our web site)

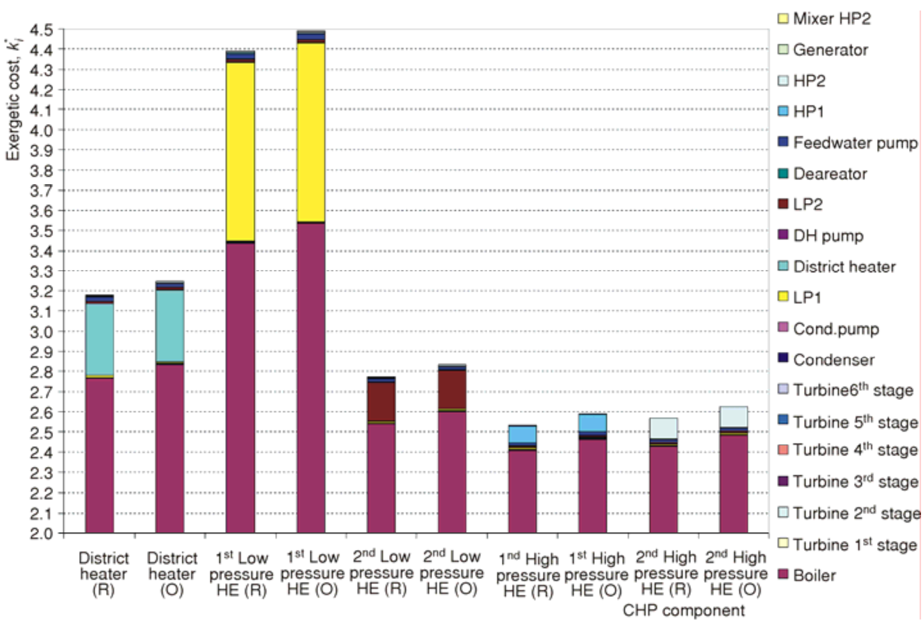

Figure 13. Comparison of reference state (R) with decreased boiler efficiency state (O) of cumulative exergetic cost in regeneration system and district heater of CHP (color image see on our web site)

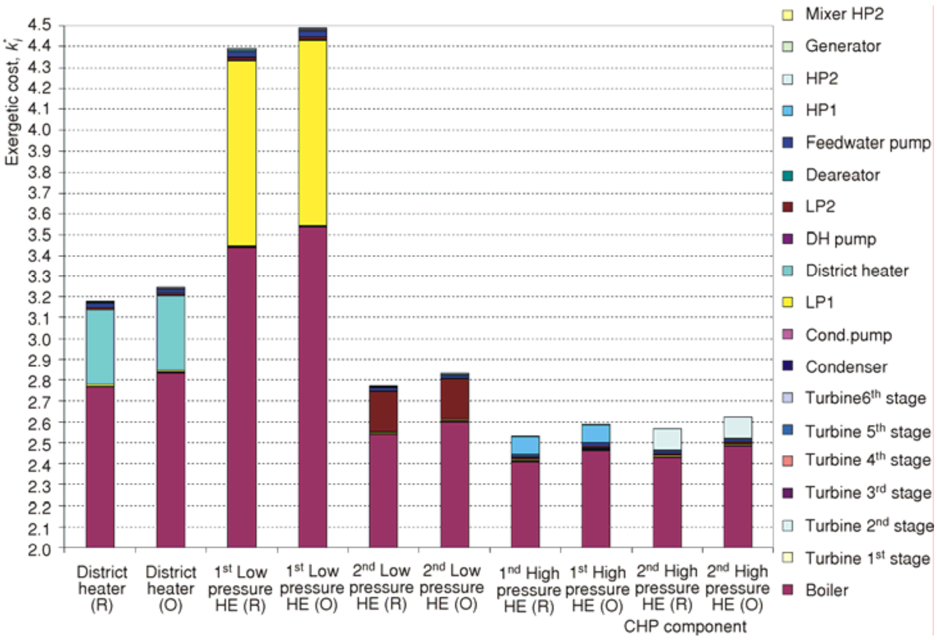

Figure 14. Comparison of reference state (R) with decreased internal efficiency of 2nd stage state (O) of cumulative exergetic cost in regeneration system and district heater of CHP (color image see on our web site)

Conclusions

The problems of energetic and exergetic evaluation of CHP plant operation with the application of mathematical modelling has been presented. The authors discuss and compared the advantages and effectiveness of two method of identification of empirical modelling: regression and neural. In both considered cases concerning models of boiler and models of turbine stages the better results have been obtained with application of neural models. The presented methods of empirical models identifications are especially useful in case when the exact physical models of energy systems or devices are very complicated or time-consuming. Besides the advantages of developed model two have to be stressed: accuracy (the correlation factor is over 90%) and short time required for computer simulations.

Moreover the authors present the problems of exergetic evaluation of CHP plant. Theoretical fundamentals of exergetic cost determination and its application were briefly discussed. The presented methodology, based on cumulative exergy calculus has been applied for the analysis of influence of operational parameters on exergetic cost indices of one of Polish CHP plant. The authors propose the model which links the algorithm of exergetic cost determination with the theoretical-empirical model of power unit. Obtained results showed that the exergetic cost is increasing progressively moving through the system from external fuels to final products. The author explained the dependence of irreversibilities of components on the exergetic cost basing on the results of calculation. It has been demonstrated that both immediate and well induced exergy losses can influence the total exergetic cost of investigated component of energy system. Moreover it has been proved with the numerical example that the induced exergy losses can have greater impact than the exact losses. The developed algorithm can be implemented for the exergy diagnosis of CHP plant.

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