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Exergetic cost of steam power plant operation

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Abstract The paper is devoted to the problems of exergetic cost determination. 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 additional possibilities ensured by the exergetic cost analysis in comparison to the direct exergy consumption analysis are discussed. The presented methodology was applied for the analysis of influence of operational parameters on exergetic cost indices of steam power plant. Results of calculations concern one of the modern Polish power plant unit. Basing on the obtained results several conclusions have been formulated that show advantages of application of exergetic cost analyses.

Keywords: Exergy; Exergetic cost; Power plant

Nomenclature

$\mathbf{A}$ – incidence matrix
$\mathbf{B}^*$ – cumulative exergy vector
a_{ij} – coefficient of consumption of i-th resource of considered j-th process
b – specific exergy, kJ/kg
b_j^*, b_i^* – specific cumulative exergy consumption burdening the production of j-th and i-th element of considered system, kJ/kg
$\dot{B}$ – exergy flow, kW
$\dot{B}^*$ – cumulative exergy flow, kW
k_j^* – cumulative exergy cost of j-th component

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$k^*_{j,i}$ – cumulative exergy cost of i-th product in j-th component
p – pressure, kPa
Δp – pressure change between operational states, kPa
Δk – increase of exergetic cost
x_0 – reference state
x_1 – operational state

Greek symbols

φ_{0j} – specific exergy of resources delivered from environment of investigated system, kJ/kg

1 Introduction

The thermal diagnosis [2,8,10,12] is used in order to identify the changes in states of the working machines, energy devices and industrial systems. Nowadays, in the field of the thermal diagnostics, there are researches on decreasing processes' energy consumption. The existing diagnosis systems have been equipped with the modules which allow to indicate causes of excessive energy consumption. A power unit represents a complex energy system [2,3]. It consists of many elements such as: boiler, turbine, regenerative heat exchangers, condenser and cooling tower. These elements are all connected and interdependent.

To estimate the influence of operating parameters on energy consumption of the electricity generation process, operating deviations of the specific heat consumption and specific energy consumption indicators are applied in the diagnosis systems. The most precise information of these deviations one can achieve by using a simulator of power plant [2,3,4]. Energy diagnosis, however useful, is not sufficient and should be supplemented with the possibility of performing exergy analysis as well as an environmental investigation.

Particular kinds of energy differ in their ability of transformation into other kinds of energy. For example [5,6], internal energy can only be partially transformed into mechanical energy. It is worth mentioning that the ability of some fluxes of matter used to drive thermal processes (for example a flux of compressed cold air), can't be characterized in the therms of energy. Moreover in comparison to energy, exergy does not satisfy the law of conservation. Every irreversible process causes an irrecoverable loss of exergy. Investigation of the influence of operational parameters on these losses plays a key role in searching elements of increased thermodynamical imperfections.

Exergy analysis is based on the application of this magnitude to the study of thermal systems [5,6]. By using this approach, the analyst can identify not only the losses of energy quantity but also the losses in energy quality (irreversibilities). The same variation of the irreversibility implies different additional consumption of resources depending on the component of the plant in which it takes place. Thermoeconomic [8] analysis goes a step forward than exergy analysis by taking into account this fact by introducing the concept of the "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 [1,8–13] is based on the concept of exergetic cost.

Consumption of the exergy connected with the fabrication of some considered product appears not only in the final stage of production but also in all plants or components of the energy-technology systems delivering semi-finished products and raw materials for the final production process [5,6]. A total consumption of the exergy of natural resources connected with the fabrication of the considered product and appearing in all of the links of the network of production process has been called "cumulative consumption of exergy". The cumulative calculus can express the total expenditure burdening the element of considered system, and is used as a base for determination 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 additional possibilities which are ensured by the exergetic cost analysis application in the comparison with the direct exergy consumption analysis are also discussed. The presented methodology is applied for the analysis of the influence of operational parameters on exergetic cost indices of steam power plant. All presented calculations were performed for an exemplary modern Polish power plant unit. Basing on the obtained results several conclusions that indicate the advantages of application of exergetic cost analyses were formulated.

2 Exergetic cost

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

- cumulative energy consumption (energy cost) [5,6],
- cumulative exergy consumption (exergy cost) [1,6],
- cumulative consumption of non-renewable natural resources (thermoecological cost) [5,6],
- cumulative emission of CO_2 (thermo-climatic cost) [7].

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

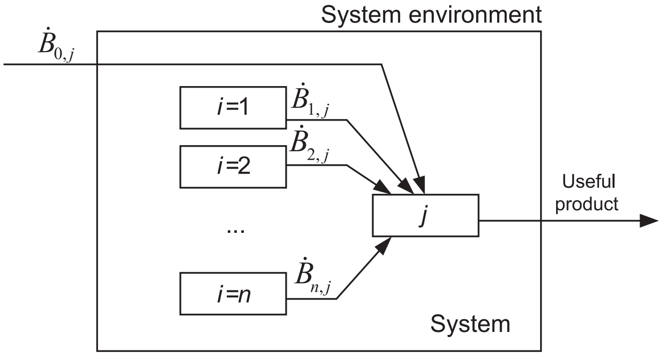

Figure 1. Connection between components of the system.

The balance equation of cumulative exergy consumption (CExC) [6] is based upon the statement that the CExC of the product of element of considered system results from the CExC burdening of the semi-finished products and by-products, and from the exergy of natural resources extracted from the nature [5,6]. Basing on this statement, Szargut proposed the general form of the cumulative exergy balance equation, which was simplified by the authors to the following from:

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

where:

b_j^*, b_i^* – specific cumulative exergy consumption burdening the production of j-th and i-th element of considered system,

a_{ij} – coefficient of consumption of i-th resource of considered j-th process,

φ_{0j} – specific exergy of resources delivered from environment of investigated system.

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:

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

This cost express a 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 a local exergetic cost expressing specific exergy consumption loco considered process. The more the exergetic cost is higher than "one" for entire chain of production processes leading to the unit under consideration, then the technological process of its production is less favorable from the viewpoint of cumulative degree of process perfection and natural resources savings.

In the case of large energy systems it is not convenient to use 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 [1,12,13]. The incidence matrix describes the connections between elements of the system and also between elements and the 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 a number of fluxes appearing within the boundary of analysed system m. The elements of incidence matrix are defined as follows:

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

Basing on the defined incidence matrix, the balance equation of exergetic cost takes the following form:

$$\mathbf{A} \cdot \mathbf{B}^* = 0 \ . \tag{3}$$

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

1. Some flows of resources are delivered to the system from the outside of the 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 introduce 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

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

where n is the numbers of cogenerated products in j-th component,

2. Some waste products are generated in the components of the system besides useful products. They represent external exergy losses. If it is not possible to use the waste products, the value of their usefulness is equal zero. In some cases their exergetic value can be negative, for example when wastes should be abated before rejection to the environment.

3. There are more than one useful products in some components of the system. Each additional product introduce additional unknown value of exergetic cost into the system of balance equations. To solve these problems the method of exergetic division of costs can be applied. In this method it is assumed [1,5,6,11] that the exergy of useful product is burdened by the same exergetic cost.

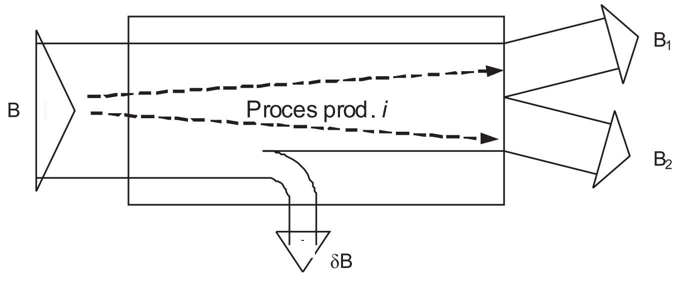

Figure 2. A simple process with two usefull products.

In the case of the component with two parallel products (Fig. 2), exergy division method (according to Eq. (5)), leads to the following equation:

$$k^*_{P1} = k^*_{P2} \ . \tag{5}$$

According to the definition of exergetic cost described by Eq. (2)

$$\frac{\dot{B}_1^*}{\dot{B}_1} = \frac{\dot{B}_2^*}{\dot{B}_2} \; . \tag{6}$$

The values of B_1 and B_2 are known from the calculation results of direct exeregic analysis of considered system or link. Introducing

$$x_1 = \frac{\dot{B}_2}{\dot{B}_1} \tag{7}$$

to the Eq. (6), additional equation in the set of equations (3), takes the form:

$$-x_1 \dot{B}_1^* + \dot{B}_2^* = 0 \; . \tag{8}$$

3 Model of the plant

For the simulative calculations of the influence of operational parameters on exergetic cost the mathematical model of the plant has to be applied. A mathematical model can be created in two different ways. One model is developed, when the physical laws are used and the analytical model is formulated. Another model can be developed based on carrying out the measurements with the application of the identification methods. In such case the empirical model is determined [2–4]. Development of measuring techniques and a computer technology ensures a wider application of the mathematical modelling of the processes basing on the registered measurement 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 especially processes of combustion and heat transfer in boilers),
- real-time optimization of the process parameters.

The models obtained from the identification of the processes have some characteristic 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,
- they are quite easy to elaborate and apply.

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

- simulate and optimise the processes,
- regulate and control the objects,
- diagnosis of the process.

A conventional power unit is a complex energy system. As it was mentioned before, such a system comprises a boiler, turbine, condenser, the regenerative heat exchangers and a cooling tower. Integration of the analytical modelling techniques with the artificial intelligence techniques in a hybrid model [2] can be considered as an useful tool which identifies complex systems. Elaborated model of a power unit contains models of: boiler, steam-water cycle and a cooling tower. Figure 3 presents a diagram of the hybrid model of a power unit.

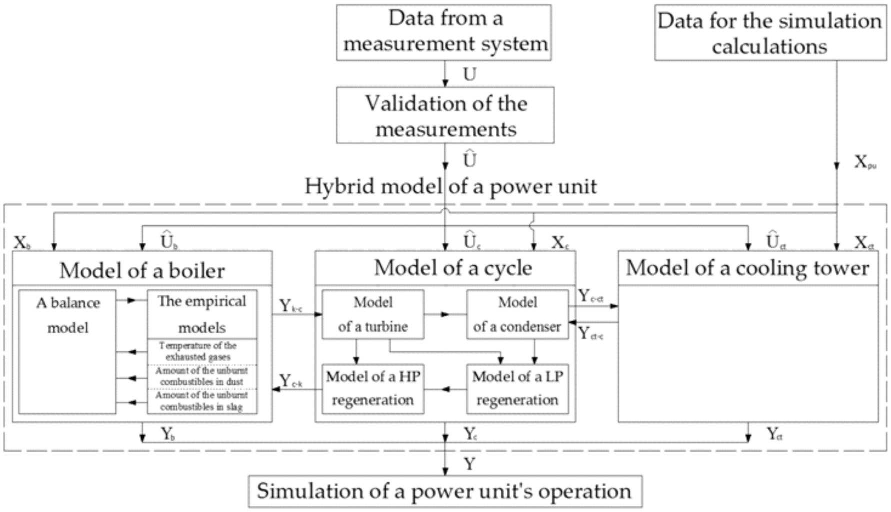

Figure 3. Diagram of the simulation model of the power unit.

The developed hybrid model of the boiler includes a balance model as well as the empirical models worked out by means of the regression and neural network based techniques. The balance model has been built based on DIN-1942 standard [3,4]. The neural network model describes the dependence between the flue gases temperature and the main operating parameters of the boiler. The regression models describing a dependence of a mass fraction of unburnt carbon in the slag and dust on the boiler operating parameters were developed with the usage of the 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 condenser [2]. 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. There are methods which use the 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. It is also possible to combine these methods. However, the flow computations demand knowledge of the flow system geometry. Such computations are time-consuming and require more complex models. The computations based on the steam flow capacity and efficiency of the process equations are simpler and less time-consuming, but require the identification of empirical coefficients of the equations.

4 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 the Polish power plants. Analyzed system is the 370 MW power unit with double steam reheat – 17.65 MPa/535 °C/535 °C. Investigated steam-water cycle includes the steam turbine, the condenser (CON), as well as high- temperature (HP1–4) and a low-temperature regeneration system (LP1–4), the feed water tank with deaerator (WT), the auxiliary turbine and pumps (AUXT). The steam turbine consists of three sections: high-pressure part (HP), medium-pressure part (MP), low-pressure part (LP), with six bleeds (Fig. 4, fluxes no. 12, (18+21), 24, 27, 29, 31). The low-temperature regeneration system contain four regenerative exchangers (i = 12–15) and is fed with the steam from the low- and medium-pressure part of the turbine. The high-temperature regeneration system comprises two parallel threads with two heat exchangers installed on each sides of the system. The heat exchangers HP3 (i = 21) and HP4 (i = 22) are fed with the steam from the outlet part of the high-pressure section of the turbine, whereas the heat exchangers HP1 ($i = 19$) and HP2 ($i = 20$) are fed with the steam from the first bleed (12) of the medium-pressure section of the turbine. The schematic diagram of the system is presented in Fig. 4.

Table 1 presents the detailed results of calculations of exergetic cost $\dot{B}^*$ of flows indicated in Fig. 4. Moreover the results of unit exergetic cost k^* are also presented. Additionally, the exergetic cost is presented in aggregated form in Figs. 5–8. The specific exergetic cost of system input resources (airflow 102 and fuel flow 101) is equal to 1 because the exergetic cost $\dot{B}^*$ of these flows was assumed to be equal to the exergy $\dot{B}$. The results presented in Tab. 1 shows that the exergetic cost is increasing progressively, moving through the system from external fuels to the final products – electricity. In the case of electricity the exergetic cost $\dot{B}^*$ takes the highest values equal to $\dot{B}^*_{119} = 1\ 009\ 729.3$ kW. In the case of electricity the specific exergetic cost is equal to $k^*_{114} = 2.67$ and is higher than specific exergtic cost of fuel k^*_{101} and specific exergetic cost of steam for example live steam $k^*_1 = 2.48$ and bleed steam $k^*_{13} = 2.52$. The increase of specific exeregtic cost through the system is caused by irreversibilities of components of chain of production. It can be observed while analyzing the results presented in the Tab. 1. These results illustrate the process of cost formation through the chain of investigated production stages.

The Tab. 1 includes results of calculations for the reference state and example operation state of the system. In the considered case the operation state is characterized by pressure rise of $\Delta p = 0.2$ kPa with respect to the pressure in condenser. The mentioned increase of pressure in condenser leads to the increase of exergetic cost of (for example):

- live steam from $k^*_1(x_0) = 2.48$ to $k^*_1(x_1) = 2.49$,
- bleed stem from $k^*_{12}(x_0) = 2.52$ to $k^*_{12}(x_1) = 2.53$,
- electricity from $k^*_{114}(x_0) = 2.67$ to $k^*_{114}(x_1) = 2.71$,
- feed water from $k^*_{70}(x_0) = 6.39$ to $k^*_{70}(x_1) = 6.45$.

It can be observed that the increase of unit exeregetic cost is higher when moving from preliminary components (bolier) $\Delta k_1 = 0.01$ to the final production stages (generator) $\Delta k_{114} = 0.04$. It is the effect of influence of cumulation of exergy losses on the cost formation through the system of production. The presented model can be also applied for sensibility analysis of exergetic cost on the influence of operational parameters of the system. The analysis of exergetic cost $\dot{B}^*$ and unit exergetic cost k^* allows us to investigate the process of cost formation while we move from the supply

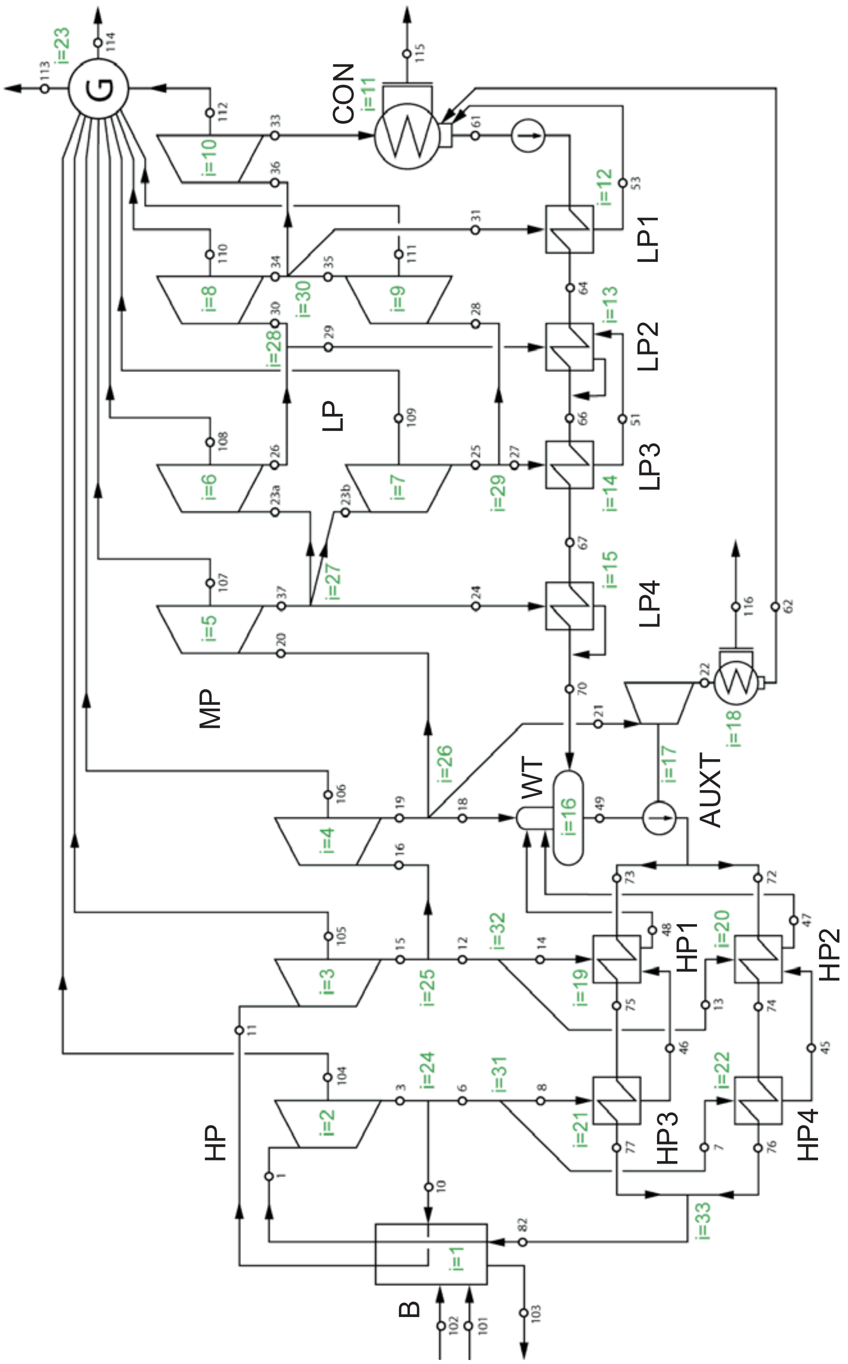

Figure 4. Schematic diagram of analyzed power plant.

Table 1. Exergetic cost.

		Reference state x_0			Operation state x_1		
	Flow	B*	B	k*	B*	B	k*
j		[kW]	[kW]	[–]	[kW]	[kW]	[–]
1	Live steam	1 183 406.5	477097.2	2.480	1 206 263.2	484 834.2	2.488
3	Interstage steam	888 335.3	358137.5	2.480	907 734.8	364 846.5	2.488
6	Bleed steam	81 941.6	33035.2	2.480	84 224.9	33 852.6	2.488
7	Bleed steam	41 873.4	16881.5	2.480	43 042.6	17 300.1	2.488
8	Bleed steam	40 068.1	16153.7	2.480	41 182.3	16 552.4	2.488
10	Interstage steam	806 393.7	325102.3	2.480	823 509.9	330 993.9	2.488
11	Reheated steam	979 012.4	405276.0	2.417	998 132.9	412 129.3	2.422
15	Outlet steam	833 616.4	345087.3	2.417	849 868.4	350 910.9	2.422
12	Bleed steam	37 107.9	14706.7	2.523	38 157.5	15 078.2	2.530
13	Bleed steam	18 060.4	7157.8	2.523	18 578.5	7 341.4	2.530
14	Bleed steam	19 047.5	7548.9	2.523	19 579.0	7 736.8	2.530
16	Interstage steam	796 508.5	330380.6	2.411	811 711.0	335 832.6	2.417
19	Outlet steam	671 741.8	278629.1	2.411	684 845.4	283 344.0	2.417
18	Bleed steam	25 188.6	10447.9	2.411	26 374.8	10 912.2	2.417
21	Bleed steam	38 420.4	15936.2	2.411	39 405.8	16 303.5	2.417
20	Interstage steam	608 132.8	252245.0	2.411	619 064.8	256 128.3	2.417
37	Outlet steam	510 523.0	211757.8	2.411	519 595.9	214 974.6	2.417
24	Bleed steam	23 223.2	9632.7	2.411	23 793.0	9 844.0	2.417
23a	Interstage steam	243 649.9	101062.6	2.411	247 901.4	102 565.3	2.417
23b	Interstage steam	243 649.9	101062.6	2.411	247 901.4	102 565.3	2.417
25	Outlet steam	209 310.0	86818.9	2.411	213 697.8	88 414.1	2.417
27	Bleed steam	30 785.9	12769.6	2.411	31 442.6	13 008.9	2.417
28	Interstage steam	178 524.1	74049.3	2.411	182 255.2	75 405.2	2.417
35	Outlet steam	87 956.7	36483.2	2.411	90 466.2	37 429.0	2.417
26	Outlet steam	144 440.2	59911.8	2.411	148 068.8	61 261.1	2.417
29	Bleed steam	9 449.4	3919.5	2.411	9 627.4	3 983.2	2.417
30	Interstage steam	134 990.8	55992.3	2.411	138 441.4	57 277.9	2.417
34	Outlet steam	96 378.1	39976.3	2.411	99 176.6	41 032.7	2.417
31	Bleed steam	8 018.9	3326.1	2.411	8 196.5	3 391.2	2.417
36	Interstage steam	176 315.9	73133.3	2.411	181 446.3	75 070.5	2.417
33	Outlet steam	92 160.0	38226.7	2.411	95 782.3	39 628.4	2.417
45	Condensate	10 128.0	4083.2	2.480	10 464.9	4 206.2	2.488
47	Condensate	10 096.0	4026.0	2.508	10 434.6	4 148.8	2.515
51	Condensate	2 934.6	1217.2	2.411	3 003.1	1 242.5	2.417
53	Condensate	362.1	150.2	2.411	370.5	153.3	2.417
61	Condensate	99 182.3	1093.6	90.692	102 972.4	1 139.0	90.403
64	Condensate	106 839.1	4107.7	26.010	110 798.5	4 209.5	26.321
66	Condensate	119 223.1	8554.3	13.937	123 429.0	8 733.1	14.133
67	Condensate	147 074.5	18096.3	8.127	151 868.5	18 443.6	8.234
70	Condensate	170 297.6	26666.9	6.386	175 661.5	27 214.9	6.455
49	Feed water	215 644.9	44648.1	4.830	222 867.4	45 607.3	4.887
72	Feed water	123 702.5	25995.9	4.758	127 726.8	26 542.9	4.812
73	Feed water	123 702.5	25995.9	4.758	127 726.8	26 542.9	4.812
74	Feed water	141 795.1	32414.5	4.374	146 335.6	33 124.5	4.418
75	Feed water	142 351.6	32633.6	4.362	146 893.5	33 343.8	4.405
76	Feed water	173 540.4	44313.8	3.916	178 913.3	45 293.2	3.950
77	Feed water	172 755.5	44027.7	3.924	178 091.5	44 994.1	3.958
82	Feed water	346 295.9	88296.8	3.922	357 004.8	90 241.7	3.956
22	Outlet steam	6 660.2	2762.6	2.411	6 819.7	2 821.5	2.417
62	Condensate	6 660.2	61.0	109.182	6 819.7	62.3	109.460
101	Fuel	1 009 729.3	1009729.3	1.000	1 023 881.4	1 023 881.4	1.000
104	Effective power	295 071.2	110546.1	2.669	298 528.4	111 805.8	2.670
105	Effective power	145 396.0	57720.7	2.519	148 264.4	58 686.3	2.526
106	Effective power	124 766.7	49608.4	2.515	126 865.6	50 272.8	2.523
107	Effective power	97 609.8	39009.6	2.502	99 468.9	39 703.0	2.505
108	Effective power	99 209.7	37140.3	2.671	99 832.7	35 940.8	2.778
109	Effective power	34 339.9	12855.5	2.671	34 203.7	12 313.7	2.778
110	Effective power	38 612.7	14455.1	2.671	39 264.8	14 135.8	2.778
111	Effective power	90 567.4	33905.0	2.671	91 788.9	33 045.0	2.778
112	Effective power	84 155.8	31504.7	2.671	85 664.0	30 840.0	2.778
113	Generator heat	0.0	0.0	1.000	0.0	0.0	1.000
114	Electricity	1 009 729.3	378237.2	2.670	1 023 881.4	378 234.8	2.707

components (boiler) of the system to the final productive components of the system (generator). It can be also observed that the returning flows (64–70) have high unit exergetic cost $k^*_{64} = 26.0$, $k^*_{66} = 13.9$, $k^*_{70} = 6.4$. It results from the relatively low values of exergy of these flows $\dot{B}_{64}$, $\dot{B}_{66}$, $\dot{B}_{70}$. We have to be aware, that in spite of rather high values of k^*_{64}, k^*_{66}, k^*_{70} the final effects of these flows are beneficial. The flow 61 (condensate form condenser) is characterized by the highest value of unit exergetic cost $k^*_{61} = 90.7$. It results from relatively low exergy of this flow ($\dot{B}_{61}= 1\ 093.6$ kW). So, the usefulness of this flux is very slight.

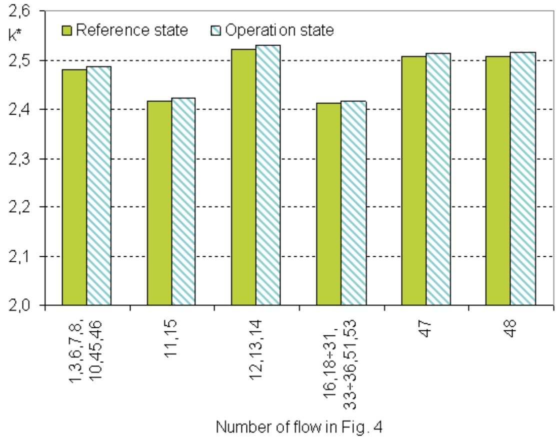

Figure 5. Exergetic cost of steam and condensate fluxes.

5 Summary

The paper concerns on the problems of exergetic cost determination. 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 steam power plants. The authors propose the model which links the algorithm of exergetic cost determination with the theoretical and empirical model of power unit. The proposed model of exergetic cost evaluation is the base for further investigation in the field of exergo-economy, which is the modern application of exergy analysis to diagnosis of thermal and technological systems.

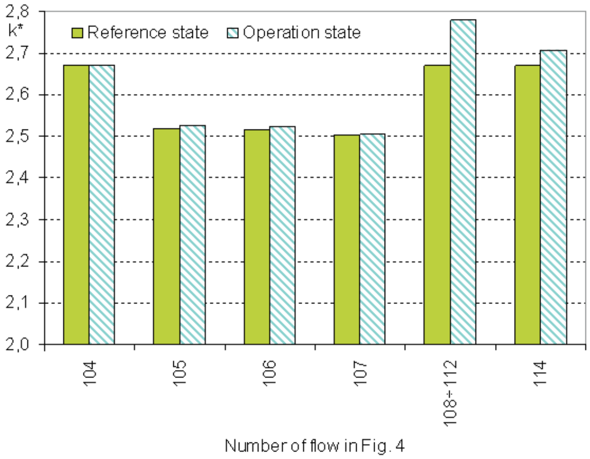

Figure 6. Exergetic cost of effective power.

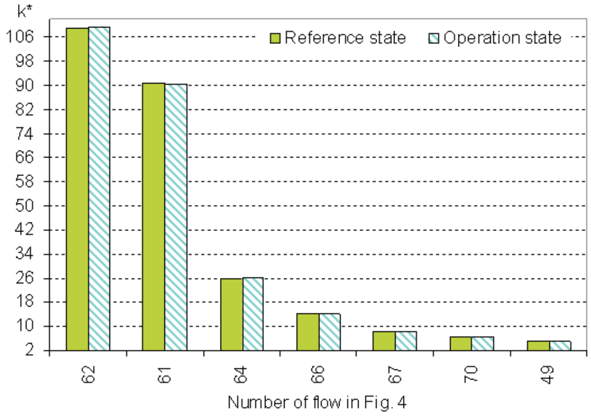

Figure 7. Exergetic cost of condensate in the low temperature regeneration system.

Obtained results showed that the exergetic cost is increasing progressively moving through the system from external fuels to final products – electricity. The author explained the dependence of irreversibilities of components on the exergetic cost basing on the results of calculation. The author pointed out that the example results of modeling presented in the paper agreeably illustrate the process of cost formation through the chain of investigated production stages.

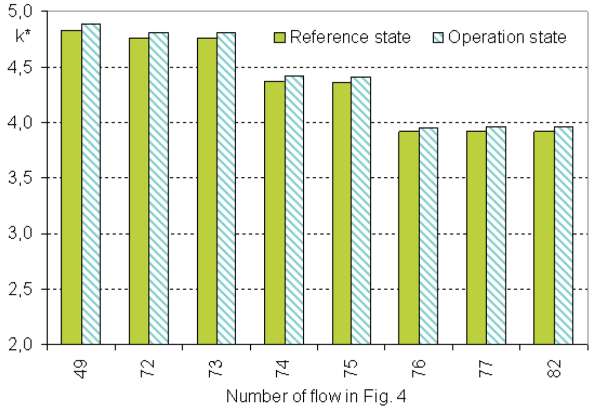

Figure 8. Exergetic cost of feed water in the high temperature regeneration system.

The results of influence of operational parameters on the exergetic cost and the cost formation were also presented. In the considered case the rise of $\Delta p = 0.2$ kPa of the pressure in the condenser has been taken into account. It can be observed that the increase of unit exeregetic cost is higher while moving from preliminary components (bolier) to final production stages (generator). It is the effect of influence of the cumulative exergy losses on the cost formation through the whole system production. The presented model can be also applied for the purpose of sensibility analysis of exergetic cost on the influence of operational parameters of the system.

Beside the investigation of exergetic cost formation, the analysis allowed to study the influence of operational parameters on the exergetic cost $\dot{B}^*$ and unit exergetic cost k^*.

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