УДК 378.65.011.56

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ADVANCED THERMODYNAMIC ANALYSIS ON EXERGY FLOW GRAFS

У статті запропоновано загальний підхід для термодинамічної аналізу систем довільної структури. Метод заснований на побудові і аналізі нового виду ексергією-топологічної моделі – ексергетичному потоковому графі і дозволив підвищити ефективність енерго-інтенсивних систем. Було показано, що процеси, які відбуваються в складних енерго-інтенсивних системах, характеризувалися взаємним перетворенням якісно різних енергетичних ресурсів. Тому термодинамічний аналіз цих систем вимагав спільного застосування обох законів термодинаміки, і, отже, ексергетичного підходу. Було показано, що одним з найбільш ефективних математичних методів, використовуваних при ексергетичної аналізі та оптимізації був метод теорії графів. Перевага графових моделей може бути також продемонстровано шляхом широкої різноманітності їх можливих додатків. Було продемонстровано застосування запропонованого підходу для термодинамічної аналізу газотурбінної установки. Було показано, що ступеня термодинамічної досконалості турбін і турбокомпресорів досить високі. Зазвичай, чим більшою була різниця між середніми параметрами робочого тіла і навколишнього середовища, тим меншими були втрати ексергії. Та ж ситуація була також вірна і для теплообмінників. Більш високий температурний рівень в регенеративної теплообміннику, в порівнянні з проміжним холодильником, та л вищу ступінь термодинамічної досконалості теплообмінника. Втрати ексергії в інших елементах системи були викликані диссипацией транспорту потоку в трубах, або механічними втратами. Було показано, що для системи в цілому ступінь термодинамічної досконалості була менше, ніж для будь-якого елемента системи через взаємного впливу елементів один на одного в системі.

Ключові слова: термодинамічний аналіз, топологічна модель, ексергетичний потоковий граф, довільна структура, оптимізація.

In the paper has been proposed f general approach for thermodynamic analysis of systems with arbitrary structures. Method was based on construction and analysis of a new type of exergy- topological model – exergy flow graph and allowed to improve the efficiency of energy intensive systems. The efficiency improving is very important problem and the main way of it solving was through thermodynamic analysis and optimization. It was shown that the processes taking place in the complex energy intensive systems were characterized by mutual transformation of quality different power resources. It has been found that one of the most effective mathematical methods used for exergetic analysis and optimization was the method the method of graph theory. The benefit of graph models can also be demonstrated by its flexibility and vide varieties of possible applications. It has been demonstrated the application of suggested approach for thermodynamic analysis of gas-turbine installation. It has been found that the degree of thermodynamic perfection of turbines and turbocompressors are sufficiently high. Usually, the bigger was the difference between average parameters of the working fluid and the environment, the smaller was the exergy losses. The same situation was also true for heat exchangers. High temperature level in regenerative refrigerator, as compared with intermediate refrigerator, give a higher degree of thermodynamic perfection of the heat exchanger. Exergy losses in other elements of the system were caused by dissipation of the flow transport in the pipelines or by mechanical losses. It has been found that for the system as a whole the degree of thermodynamic perfection was less than the same characteristics for any element of the system in result of the mutual influence of the element on the other in the system

Keywords – thermodynamic analysis, topological model, exergy flow graph, arbitrary structures, optimization.

В статье предложен общий подход для термодинамического анализа систем произвольной структуры. Метод основан на построении и анализе нового вида эксерго-топологической модели – эксергетическом потоковом графе и позволил повысить эффективность энерго-интенсивных систем. Было показано, что процессы, имеющие место в сложных энерго-интенсивных системах, характеризовались взаимным превращением качественно различных энергетических ресурсов. Поэтому термодинамический анализ этих систем требовал совместного применения обоих законов термодинамики, и, следовательно, эксергетического подхода. Было показано, что одним из наиболее эффективных математических методов, используемых при эксергетическом анализе и оптимизации являлся метод теории графов. Преимущество графовых моделей может быть также продемонстрировано путем широкого разнообразия их возможных приложений. Было продемонстрировано применение предложенного подхода для термодинамического анализа газотурбинной установки. Было показано, что степени термодинамического совершенства турбин и турбокомпрессоров достаточно высоки. Обычно, чем большей была разность между средними параметрами рабочего тела и окружающей среды, тем меньшими были потери эксергии. Та же ситуация была также верна и для теплообменников. Более высокий температурный уровень в регенеративном теплообменнике, по сравнению с промежуточным холодильником, дал более высокую степень термодинамического совершенства теплообменника. Потери эксергии в других элементах системы были вызваны диссипациями транспорта потока в трубах, или механическими потерями. Было показано, что для системы в целом степень термодинамического совершенства была меньше, чем для любого элемента системы из-за взаимного влияния элементов друг на друга в системе.

Ключевые слова*:* термодинамический анализ, топологическая модель, эксергетический потоковый граф, произвольная структура, оптимизация.

Introduction

In the design and operation of energy intensive systems, the possibility of improving the system's efficiency is very important to explore. The main way of improving efficiency is through thermodynamic analysis and optimization.

The processes taking place in the complex energy intensive systems are characterized by mutual transformation of quantitatively different power resources. For this reason, the thermodynamic analysis of these systems requires the combined application of both laws of thermodynamics and demands the exergy approach [1, 2].

These methods are universal and make it possible to estimate the fluxes and balances of all energy flows for every element of the system using a common criterion of efficiency.

Despite its usefulness, the benefits of the exergetic approach were not fully realized until recent years. One reason for this situation is the underestimation of exergetic functions for mathematical modeling synthesis, and optimization of flow sheets. Another reason is the mathematical difficulty of the exergetic approach in thermodynamic analysis. Meanwhile, the increasing complexity of optimization problems requires more effective and powerful mathematical methods. Hence, during the last few years, many papers with different applications of thermodynamic methods have been published (see for example [3–10]).

The above referenced papers, as well as the author's earlier investigations [11–15] show that one of the most effective mathematical methods used for exergetic analysis and optimization is the method of graph theory [17, 18]. The benefit of graph models can also be demonstrated by its flexibility and wide varieties of possible applications.

The exergy topological method is based on the combination of exergy flow graph, exergy losses graph and thermoeconomical graphs. In this article will be used the exergy flow graph.

1. The exergy flow graph and its properties

The exergy flow graph of a system with arbitrary structure can be expressed as a graph, $E=(A,\Gamma)=(A,U)$, where A is nodes multitude corresponds to systems elements $A=\{a_1,a_2,\dots,a_i,\dots,a_m\}$, U is the arcs multitude corresponds to the exergy flows distribution in the system $U=\{a_i,a_l\}; i\neq 1; i=1,2,\dots,m; l=1,2,\dots,m$, and Γ represents a multivalued display of multitude A into itself. The main properties of the exergy flow graph $E=(A,\Gamma)$ are as following:

Property 1. Exergy flow $E(A,\Gamma)$ is linked.

Proof Assume that property 1 is wrong and $\exists a_k\in A$, that $\Gamma a_k=0$ and $\Gamma^{-}a_k=0$. Then the changing of parameters in the a_k -element will not influence at behaviour of the system as a whole. In these case based on the definition of the system [2], $a_k\notin A$. But since it is assumed that $a_k\in A$. This contradiction proves that *Property 1* is true.

When applying the graph to a real system, linking of exergy flow graph means that every element of the system has flows tied with at least one another element.

Property 2 Exergy flow graph is directed:

$$(\forall a_k\in A,\forall a_1\in A)\Rightarrow(a_k,a_1)\neq(a_1,a_k).$$

Proof. Assume that property 2 is wrong and

$$(\exists a_k\in A,\exists a_1\in A)\Rightarrow(a_k,a_1)=(a_1,a_k).$$

Then the order of follows of such elements in the system (which determine the technology of process) can be arbitrary. That is impossible.

Property 3 Exergy flow graph of system with arbitrary structure $E=(A,U)$ is antisymmetric in general case:

$$(\exists a_k\in A,\exists a_1\in A),(a_k,a_1)\in U\Rightarrow(a_1,a_k)\notin U.$$

Proof Assume that property 3 is wrong and

$$(\forall a_k\in A,\forall a_1\in A),(a_k,a_1)\in U\Rightarrow(a_1,a_k)\in U.$$

Then every pair of elements is tied with recycle flows. It is in general case not true.

Property 4 Exergy flow graph $E=(A,\Gamma)$ is not strictly tied in general case: $(\exists a_k\in A)\hat{\Gamma}a_k\neq A)$, where $\hat{\Gamma}$ is the transitive close, $\hat{\Gamma}=\Gamma a_k U\Gamma^2 a_k U\dots U\Gamma^n a_k$.

Proof The proof is the same as that of property 3.

Property 5 Exergy losses in any a node of the exergy flow graph $E=(A,\Gamma)$ are determined by algebraic sum of arcs positively and negatively incidental to this node

$$\Pi_k=U^{+}-U^{-}.$$

Proof Assume that property 5 is wrong $\Pi_k\neq U^{+}-U^{-}$. Then the sum of exergy losses will not be equal to the differ between exergies inlet and outlet flows from the element. It is in contradiction with results of the exergy balances of system. This contradiction proves property 5 is true.

Property 6 Exergy flow graph $E=(A,\Gamma)$ is generalised for existing types of flow graphs.

Proof Assume that property 6 is wrong.

Then exists some flow graphs $\hat{E}=(\hat{A},\hat{\Gamma})$which include itself as a single case graph $E=(A,\Gamma)$ (let us remind that in this article only thermodynamic characteristics is discussed, the economic one will be considered later). Then flows on arcs of graphs $E=(A,\Gamma)$ and $\hat{E}=(\hat{A},\hat{\Gamma})$ will be different. At least the varies of one thermodynamic parameter will not influence the exergy of flows (in opposite case this parameter was accounted by graph $E=(A,\Gamma)$). But there is no such thermodynamic parameter because exergy takes into account all the thermodynamic parameters. This contradiction proves property 6 is true.

Existing types of flow graphs include material heat and parametric flow graphs. Nodes on these flow graphs represents single element which change the corresponding characteristic of the system (such as material or heat flow, etc.). Arcs on these graphs correspond to the distribution of flows (heat, material, parametric etc.). For fully description of the system, it is necessary to build and consider all these flow graphs together.

Building of these graphs is a tedious and difficult process for large systems. It is necessary to consider these graphs together, because the result of describing only one feature of multi-factors process in the system does not provide the general information about the system in general.

The generalisation of characteristic and exergy flow graph gives the possibility to avoid multi-types of graph models in analysis of power intensive systems. Also it provides a common exergy-topological approach in the systems investigation.

In this article, is given the use of exergy flow graph for receiving main exergetic characteristic for system with arbitrary structure particularly for seeking exergy losses in any element of the system and the system as a whole.

From the point of thermodynamics, the value of exergy losses in any element shows the importance of the element and provides possible ways to the improvement of the system. Sum of all element exergy losses of the system provides an objective function for optimisation.

Besides that, the exergy losses can also be used as a part of thermoeconomical criteria in technical economical analysis of the system.

The structure of the exergy flow graph and hence the structure of a modelling system are uniquely described by matrix of incidence [17]. Elements of the matrix may have one of three meanings: 0 – means that j-flow and i-element are not tied, 1 – means that j-flow enters i-element, 1 – means that j-flow leaves i-element.

2. Outline of model for determination of the exergy losses (EXL model).

A model EXL for the determination of exergy losses for a system of arbitrary structure is given in Fig. 1.

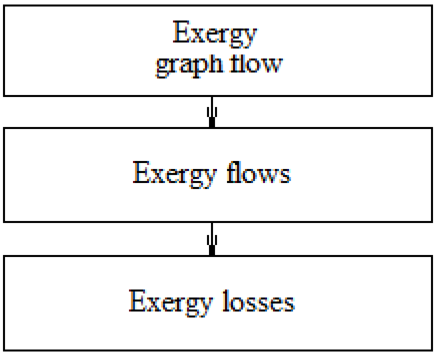

Fig.1. Model EXL

Using the rules mentioned above, exergy flow graph $E = (A, U)$ and its matrix of incidence corresponding to the system under consideration are built in the first block.

The recognising procedure for the types of flows on arcs on graph $E = (A, U)$ and for calculation of their exergies are made in the second block. While considering the thermal power systems, the exergy flows of four types [2]: exergy of mass-flow, exergy of heat-flow, exergy of work and exergy of fuel are illustrated.

Specific mass exergies of these four types are calculated by the equations given in [2].

Then, $E_i^{вп} E_i^{вх}$ – the sum of exergy flows corresponding to those at the inlet and outlet from i-element are formed. After that in the third block it is easy to show: exergy losses in i-element of the system

$$\Pi_i = E_i^{вп} - E_i^{вх}; \qquad (1)$$

degree of thermodynamic perfection

$$\nu_i = \frac{E_i^{вх}}{E_i^{вп}} = 1 - \frac{\Pi_i}{E_i^{вп}}; \qquad (2)$$

and exergy losses of the system as a whole

$$\Pi_\Sigma = \sum_{i=1}^{n} \Pi_i \qquad (3)$$

From the result of the calculation, the meanings of exergy losses Π_i and degrees of thermodynamic perfection ν_i for every element of the system as well as the summary exergy losses for the system as a whole Π_Σ can be obtained.

3. Thermodynamic analysis of gas turbine installation

The algorithm EXL described above was applied for thermodynamic analysis of a gas-turbine installation. In Fig. 2: I-filter, II- turbo-compressor, III- intermediate refrigerator, IV- high pressure turbocompressor, V- high pressure turbine, VI- combustion chamber, VII- regenerative heat exchanger, VIII- average pressure turbine, XI- low pressure turbine, X- generator.

The exergy flow graph for this flowsheet is given in Fig. 3, the matrix of incidence in Fig. 4.

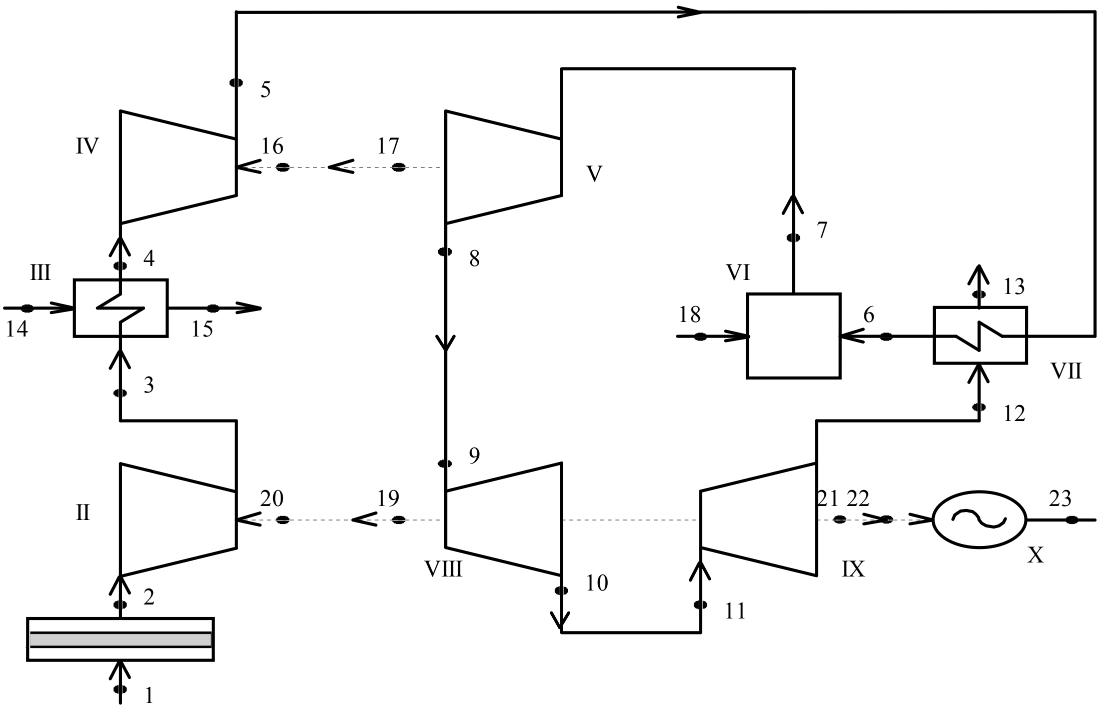

Fig.2. Flowsheet of gas-turbine installation

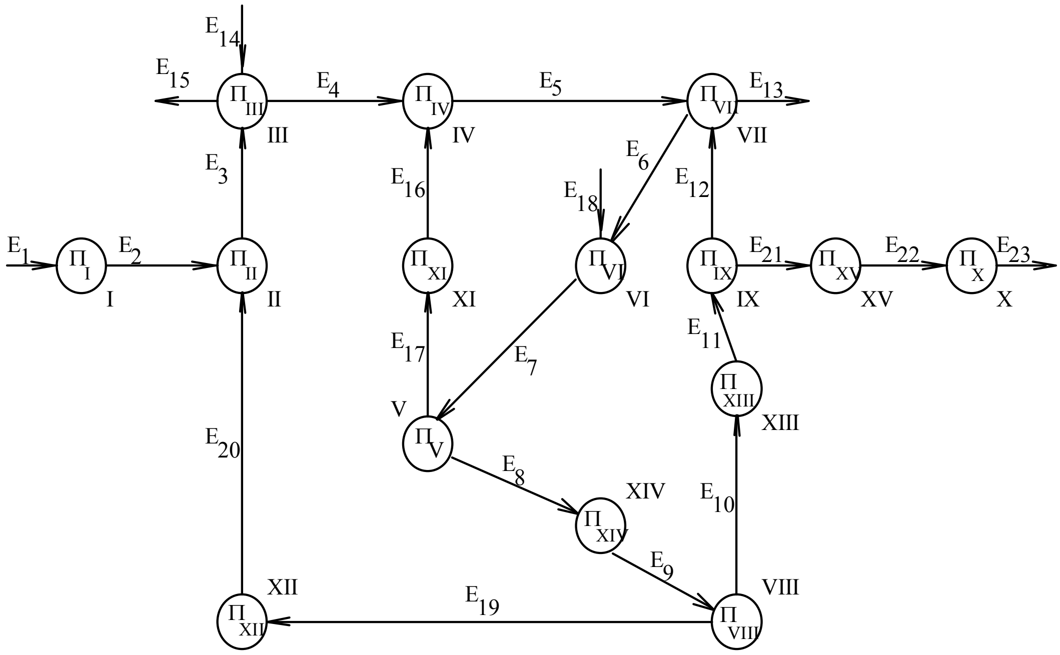

Fig. 3. Exergy flow graph corresponding to the flowsheet in Fig.2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I	1	-1																					
II		1	-1																	1			
III			1	-1										1	-1								
IV				1	-1											1							
V							1	-1									-1						
VI						1	-1											1					
VII					1	-1						1	-1										
VIII									1	-1									-1				
IX											1	-1									-1		
X																						1	-1
XI																-1	1						
XII																				-1			
XIII										1	-1												
XIV								1	-1														
XV																					1	-1	

Fig. 4. Matrix of incidence of the exergy flow graph shown in Fig.3

Parameters of the flows were calculated in [18] and given in Table 1.

Exergy of flows was calculated by formulas given in [3] with such approximations: exergy of fuel equal heat value Q_c^w, exergies of mass flows $e_j = (h_j - h_0) - T_0(s_i - s_0)$, where $P_0 = 0.1\ MPa$, $T_0 = 273.15\ K$. The reason for such approximation is to simplify the procedure of calculation. The chemical exergy of flows in gas-turbine installation $(e_j^{ch} = 0)$ is ignored in the illustrated example, because even for combustion gases the amount of chemical exergy in full exergy of flow is usually less than 1% [3]. Besides, e_j^{ch} is not used in any element of the system and become a loss outside of the installation.

In the installation as shown in Fig.2, air with mass flow rate M_I and parameters P_I, t_I enters filter *I*, where its pressure is throttled down from P_I to P_2. After that, air is compressed in turbocompressor II with a consumption of capacity $N_{II} = M_2(h_3 - h_2) = 2.72\ MW$ to parameters P_3 and t_3 (the driver for turbocompressor II is a turbine of average pressure VIII which sets on the same shaft with the compressor).

Air then enters to intermediate refrigerator III. In refrigerator III air is chilled by water (water is heated from t_{14} to t_{15}) to parameters P_4 and t_4. Air is then compressed by the high pressure compressor IV with a consumption of capacity $N_{IV} = M_4(h_5 - h_4) = 2.26\ MW$ to parameters P_5 and t_5 (the driver for turbocompressor IV is a turbine of high pressure which sets on the same shaft as a turbocompressor is). Air enters a regenerative heater VII and is heated to parameters P_6 and t_6. The products of combustion are chilled from t_{12} to t_{13}.

Then the heated air passes to the combustion chamber where a full combustion (flow 18, $Q_c^w = 11.56\ MJ/m^3$) occurs. The products of combustion are formed (mass flow rate M_7, temperature t_7, pressure P_7). It enters the turbines of high (V), average (VIII), and low pressures (IX) successively, and expands with the removal of capacity

$$N_V = M_8(h_7 - h_8) = 2.54\ MW \quad (4)$$

$$N_{VII} = M_9(h_{10} - h_9) = 2.94\ MW \quad (5)$$

$$N_{IX} = M_{11}(h_{11} - h_{12}) = 3.05\ MW \quad (6)$$

The difference of parameters in points 8, 9 and 10, 11 are due to throttling in the pipe-lines.

Exergy losses in the turbines and in the turbocompressor are the result of dissipation of expansion (pressure) processes in a real installation. Degree of thermodynamic perfection of turbines and turbocompressors are sufficiently high. Usually, the bigger the difference between average parameters of the working fluid and the environment, the smaller the exergy losses.

The same situation is also true for heat exchangers. Higher temperature level in regenerative refrigerator VII (as compared with intermediate refrigerator III) gives a higher degree of thermodynamic perfection of the heat exchanger $\nu_{II} = 0.855$ as compared with $\nu_{III} = 0.699$.

Table1 Parameters of flows in the flowsheet of gas-turbine installation in Fig.2

Number of flow	Temperature $t, °C$	Pressure P, MPa	Enthalpy $h, kJ/kg$	Entropy $S, kJ/kgK$	Mass flow rate $M, kg/s$	Specific exergy $e, kJ/kg$	Exergy E, MW
1	15	1.01	15.1	0.216	27.00	-43.9	-1.18
2	15	0.98	15.1	0.225	27.00	-46.3	-1.25
3	115	2.42	115.9	0.257	27.00	45.9	1.24
4	25	2.38	25.2	0.009	27.00	22.8	0.62
5	108	4.96	108.9	0.045	27.00	96.7	2.60
6	314	4.84	329.8	0.522	27.00	137.3	5.05
7	684	4.64	738.2	1.066	27.95	446.9	12.49
8	606	3.24	647.4	1.079	27.95	353.3	9.87
9	606	3.13	647.4	1.091	27.95	349.9	9.78
10	511	1.94	542.1	1.102	27.95	241.5	6.75
11	511	1.92	542.1	1.107	27.95	240.2	6.72
12	412	1.09	432.9	1.126	27.95	124.9	3.49
13	212	1.02	218.8	0.768	27.95	5.7	0.16
14	15	0.30	63.2	0.224	19.50	2.1	0.04
15	45	0.30	188.5	0.638	19.50	14.2	0.28
16	-	-	-	-	-	-	2.26
17	-	-	-	-	-	-	2.54
18	20	0.59	34.7	0.580	0.95	12600	11.93
19	-	-	-	-	-	-	2.94
20	-	-	-	-	-	-	2.72
21	-	-	-	-	-	-	3.05
22	-	-	-	-	-	-	2.90
23	-	-	-	-	-	-	2.81

Table2. Thermodynamic characteristics of gas-turbine installation in Fig.2

No	Name of element	Number of corresponding node of graph	Sum of exergies flows		Exergy losses in element Π_i, MW	Degree of thermodynamic perfection ν_i
			at inlet to element $E_i^{вп}, MW$	at outlet from element $E_i^{вх}, MW$		
1	2	3	4	5	6	7
1	Filter	I	-1.18	-1.25	0.07	0.940
2	Turbo-compressor	II	1.47	1.24	0.23	0.843
3	Intermediate refrigerator	III	1.28	0.90	0.39	0.699
4	High pressure turbo-compressor	IV	2.88	2.60	0.28	0.902
5	High pressure turbine	V	12.49	12.41	0.08	0.933
6	Combustion chamber	VI	16.98	12.49	4.49	0.733
7	Regenerative heat exchanger	VII	6.09	5.21	0.88	0.855
8	Average pressure turbine	VIII	9.78	9.69	0.09	0.990
9	Low pressure turbine	IX	6.72	6.54	0.18	0.973
10	Generator	X	2.90	2.81	0.09	0.968
11	Drive of high pressure turbo-compressor IV	XI	2.54	2.26	0.28	0.889
12	Drive of turbo-compressor II	XII	2.94	2.72	0.22	0.925
13	Pipe-line tying turbines VIII and IX	XIII	6.75	6.72	0.03	0.995
14	Pipe-line tying turbines V and VIII	XIV	9.87	9.78	0.09	0.990
15	Generator drive	XV	3.05	2.90	0.15	0.950

Exergy losses in other elements of the system are caused by dissipation of the flow transport in the pipe-lines (elements XIII, XIV) or by mechanical losses (elements XI, XII, XV). For the system as a whole

$$E_\Sigma^{вп} = E_1 + E_{14} + E_{18} = 10.841\ MW \quad (7)$$

$$E_\Sigma^{вх} = E_{15} + E_{13} + E_{23} = 3.246\ MW \quad (8)$$

$$\Pi_\Sigma = 7.595\ MW \quad (9)$$

The degree of thermodynamic perfection $\nu_\Sigma = E_\Sigma^{вх}/E_\Sigma^{вп} = 0.299$ is less than the same characteristics for any element of the system in result of the mutual influence of one element on the other in the system.

4. Conclusion

A special model for advanced thermodynamic is presented. This general approach for thermodynamic system analysis is based on special properties of exergy flow graph. The model can be constructed for any energy- intensive system and is invariant for technological aim and structure of the system. For this reason, the model can be applied for the investigation of various energy intensive systems in different branches of industry. As illustrative example the thermodynamic analysis of gas-turbine installation is given.

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Поступила (received) 23.05.2016

Бібліографічні описи / Библиографические описания / Bibliographic descriptions

Розширений термодинамычний аналіз ексергетичних потокових графів / В. Р. Нікульшин, А. Є. Денисова, **А. С. Денисова** // Вісник НТУ «ХПІ». Серія: Інноваційні дослідження у наукових роботах студентів. – Х. : НТУ «ХПІ», 2017. – № 41(1263). – С. 10–16. – Бібліогр.: 18 назв. – ISSN 2220-4784.

Advanced thermodynamic analysis on exergy flow grafs / *Vladimir Nikulshin, Alla Denysova, Anastasiia Denysova* // Bulletin of National Technical University «KhPI». Series: Innovation researches in students' scientific work. – Kharkiv: NTU «KhPI», 2017. – № 41(1263). – p. 10–16. Bibliog.:18 titles. – ISSN 2220-4784.

Расширенный термодинамический анализ эксергетических потоковых графов / В. Р. Никульшин, А. Е. Денисова, **А. С. Денисова** // Вісник НТУ «ХПІ». Серия: Инновационные исследования в научных работах студентов. – Х. : НТУ «ХПІ», 2017. – № 41(1263). – С. 10–16. – Бібліогр.: 18 назв. – ISSN 2220-4784.

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