Thermodynamic analysis of energy intensive systems on exergy flow graphs

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Abstract. The main way of energy intensive systems efficiency improving is thermodynamic analysis and optimization. This paper describes a general approach for thermodynamic analysis of systems with arbitrary structures. Method is based on construction and analysis of a new type of topological model-exergy flow graph and illustrated on example of gas-turbine installation thermodynamic analysis.

***Keywords**: thermodynamic analysis, exergy, flow graphs.*

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].

Hence, during the last few years, many papers with different applications of thermodynamic methods have been published (see for example [2-9].

The above referenced papers, as well as the author's earlier investigations [10-13] show that one of the most effective mathematical methods used for exergetic analysis and optimization is the method of graph theory [14].

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

The exergy flow graph. The exergy flow graph of a system with arbitrary structure[11] can be expressed as a graph, E =(A, Γ)= (A, U), where A is nodes multitude corresponds to systems elements A={a_1 ,a_2 ,...,a_i ,...,a_m }, U is the arcs multitude corresponds to the exergy flows distribution in the system U={a_i ,a_l}; $i \neq l$; i = 1, 2, ..., m; l = 1,2, ..., m;, and Γ represents a multivalued display of multitude A into itself.

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 on example of gas turbine installation is given the use of exergy flow graph for receiving main exergetic characteristic for systems with arbitrary structure, particularly for calculation exergy losses in any element of the system and the system as a whole.

Algorithm EXP. Algorithm for determination of exergy losses consists from three main steps.

Step 1. Building the exergy flow graph.

Step 2.Calculation the exergy flows.

Step 3. Calculation the exergy loses.

For the thermal power systems the exergy flows of four types can be under consideration : exergy of mass-flow, exergy of heat-flow, exergy of work and exergy of fuel. Specific mass exergies of these four types are given in [1].

Then, E_i^{en} E_i^{ex} -the sum of exergy flows corresponding to those at the inlet and outlet from i-element are formed and the exergy losses in i-element of the system is:

$$\Pi_i = E_i^{en} - E_i^{ex} \quad (1)$$

Degree of thermodynamic perfection

Thermodynamic analysis of gas turbine installation

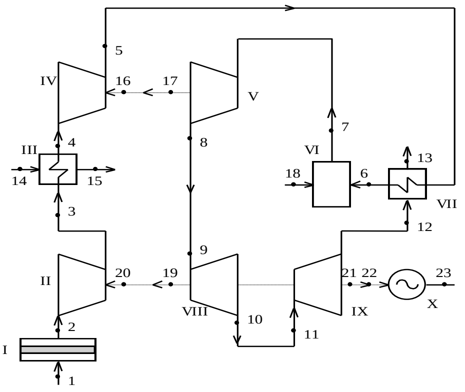

Fig. 1 Flowsheet of gas-turbine installation

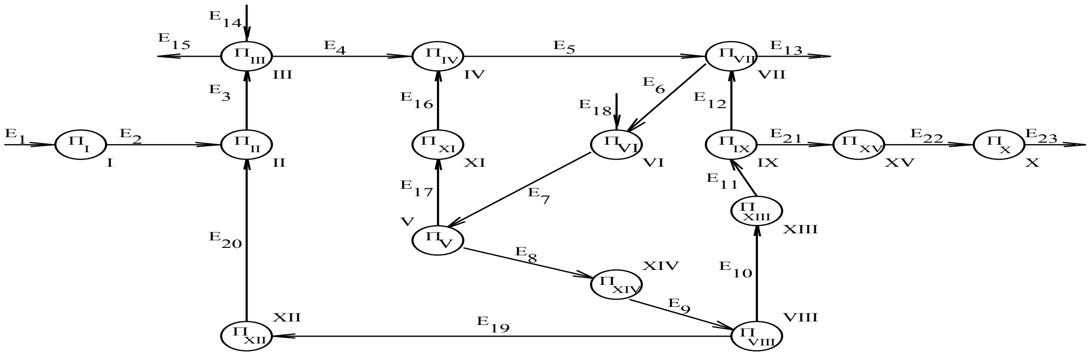

Fig. 2 Exergy flow graph corresponding to the flowsheet in Fig.1

$$
\begin{array}{r|ccccc|ccccc|ccccc|ccccc|ccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 19 & 20 & 21 & 22 & 23 \\
\hline
I & 1 & -1 & & & & & & & & & & & & & & & & & & & & & \\
II & & 1 & -1 & & & & & & & & & & & & & & & & & 1 & & & \\
III & & & 1 & -1 & & & & & & & & & & 1 & -1 & & & & & & & & \\
IV & & & & 1 & -1 & & & & & & & & & & & 1 & & & & & & & \\
V & & & & & & & 1 & -1 & & & & & & & & & -1 & & & & & & \\
\hline
VI & & & & & & 1 & -1 & & & & & & & & & & & 1 & & & & & \\
VII & & & & & 1 & -1 & & & & & & 1 & -1 & & & & & & & & & & \\
VIII & & & & & & & & & 1 & -1 & & & & & & & & & -1 & & & & \\
IX & & & & & & & & & & & 1 & -1 & & & & & & & & & -1 & & \\
X & & & & & & & & & & & & & & & & & & & & & & 1 & -1 \\
\hline
XI & & & & & & & & & & & & & & & & -1 & 1 & & & & & & \\
XII & & & & & & & & & & & & & & & & & & & & -1 & & & \\
XIII & & & & & & & & & & 1 & -1 & & & & & & & & & & & & \\
XIV & & & & & & & & 1 & -1 & & & & & & & & & & & & & & \\
XV & & & & & & & & & & & & & & & & & & & & & 1 & -1 & \\
\hline
\end{array}
$$

Fig. 3 Matrix of incidence of the exergy flow graph shown in Fig.2

$$\nu_i = \frac{E_i^{ex}}{E_i^{en}} = 1 - \frac{\Pi_i}{E_i^{en}} \quad (2)$$

and exergy losses of the system as a whole

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

Table 1. Parameters of flows in flowsheet of gas-turbine installation in Fig.1

Number of flow	Temperature t, ^{0}C	Pressure P, MPa	Enthalpy h, kJ/kg	Entropy S, kJ/kg K	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

Table 2. Thermodynamic characteristics of gas-turbine installation in Fig.1

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^{en}, MW	at outlet from element E_i^{ex}, 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

The algorithm EXP described above was applied for thermodynamic analysis of a gas-turbine installation in Fig.1. The exergy flow graph for this flowsheet is given in Fig. 2, the matrix of incidence in Fig. 3.

Parameters of the flows were calculated in [15] and given in Table 1.

Exergy of flows was calculated by formulas given in [1] 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 then 1% [1]. Besides that, 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.1, 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 (4)

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

$N_{IX} = M_{11}(h_{11} - h_{12}) = 3.05$ MW (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 turbo compressor 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 $\nu_{III} = 0.699$.

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

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

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

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

The degree of thermodynamic perfection $\nu_\Sigma = E_\Sigma^{ex} / E_\Sigma^{en} = 0.299$ 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.

Conclusion. A special model for advanced thermodynamic analysis 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. Illustrative example of gas-turbine installation thermodynamic analysis is given.

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Термодинамический анализ энергоинтенсивных систем на эксергетических потоковых графах

В. Никульшин

Аннотация. Основным путем повышения энергоэффективности энергоинтенсивных систем является их термодинамический анализ и оптимизация. В статье описан общий подход к термодинамическому анализу систем произвольной структуры. Метод базируется на построении и анализе нового типа топологических моделей-эксергетическом потоковом графе. Приведен пример термодинамического анализа газо-турбиной установки.

Ключевые слова: *термодинамический анализу, эксергия, потоковый граф.*