THERMODYNAMIC ANALYSIS OF AIR REFRIGERATOR ON EXERGY GRAPH

by

Vladimir NIKULSHIN, Margaret BAILEY, and Viktoria NIKULSHINA

Original scientific paper
UDC: 66.045.5:536.77
BIBLID: 0354-9836, *10* (2006), 1, 99-110

Improving mechanical system efficiency is the goal of many engineers and scientists. Commonly, the solutions to these types of problems are uncovered using thermodynamic analysis and optimization. An innovative method for the thermodynamic analysis of a complex energy-intensive system with an arbitrary structure is described in this paper. The method is based on a novel general equation to calculate the total system exergy efficiency using an exergy flow graph proposed by the authors. Discuss in this paper exergy efficiency and exergy loss models as well this approach allows a user to obtain not only the exergy losses and efficiency of the total system, but also to show the relationship between the exergy efficiency of an individual element and that of the entire system. An example is provided that employs this method to the thermodynamic analysis of an air refrigerator.

Key words: *thermodynamic analysis, exergy, efficiency, air refrigerator*

Introduction

A new method of thermodynamic exergetic investigation has recently been introduced in power, heat, and chemical technology as well as other fields [1-3]. In contrast to the traditional methods of thermodynamic investigation, the exergetic method takes into account both quantity and quality of energy flow. The quality of energy is often considered an even more important characteristic function than the quantity of energy in an energy system analysis. One advantage of the qualitative or exergetic method is its universality which makes it possible to estimate the flux and balance of all kinds of energy for every element of the system using a common criterion. Therefore, this method is helpful in energy system analysis and calculation. A second important feature of the exergetic method is its direct tie with the technical-economical characteristics of a system. The economic investigation, which is based on exergy optimization, covers a wide area of topics of thermodynamic system optimization and is known as thermoeconomics. The use of exergy permits one to choose the objective criterion for the analysis and optimization of systems. As a result, exergy and its functionality work very well in system analysis.

Despite its usefulness, the exergetic approach was not fully realized until recently. One reason for this situation is its underestimation of exergetic functions for mathematical modeling, syntheses, and optimization of flow sheets. Another possible reason for the delay in widespread use of exergetic analysis is its mathematical complexity associated with thermodynamic analyses. Meanwhile the increasing complexity of optimization requires more effective and powerful mathematical methods. Hence, during the last few years, many papers in exergy [4-13] with different applications have been published. The review of these papers and the author's investigations [14-20] have revealed that the most effective mathematical approach to an exergetic analysis and optimization problem is the method of graphs theory [21].

The approach of graphs theory has a very wide range of applications in different branches of science (mathematics, chemistry, electricity, economy, and even in linguistics and genetic) because of its clearness and vivid language of illustration. This approach is very effective in systems investigations due to binary connections between the elements (of any multitude) as displayed by graphs. The graphs theory method is attractive for solving optimization problems using computers because rather difficult real problems can be modeled and solved using a concise algorithm. Consequently, the most effective way of solving problems of thermodynamic analysis and optimization of flow sheets is to pair the method of exergetic analyses with a mathematical method of graphs theory. The combined exergy-graphs method which is referred to as the exergy-topological method by the authors [14-16] is herewith described.

The exergy-topological method is based on the combination or solely use of exergy flow graphs, exergy loss graphs, and thermoeconomical graphs. The usage of appropriate exergy-topological model depend on goal of investigation. If thermodynamic functions are enough can be employed exergy flow or exergy losses graphs. If it is necessary to take into account economic characteristics have to be used thermoeconomical graphs. In this paper the exergy flow graph model is employed.

The exergy flow graph of a system with arbitrary structure can be expressed as a graph expressed by eq. (1):

$$E = (A, \Gamma) = (A, U) \tag{1}$$

where A – a multitude including all nodes (elements of the system) corresponds to $A = \{a_1, a_2, ..., a_i, ..., a_m\}$, U – a multitude of arcs represents all of the exergy flows distributions in the system where $U = \{a_i, a_k\}$; i k; $i = 1, 2, ..., m$; $k = 1, 2, ..., m$, and Γ – represents a multiciphered valued display of A into itself. All properties of the exergy flow graph $E = (A, \Gamma)$ are explained in details and proved in papers [14-16].

The structure of the exergy flow graph and the structure of a modeling system are then uniquely described by a matrix of incidence [21]. Elements of the exergy-flow graph matrix of incidence may have one of the three meanings listed below:

0 – corresponds to a condition where the j^{th} flow and i^{th} element are not tied,
+1 – corresponds to a condition where the j^{th} flow enters the i^{th} element, and (2)
–1 – corresponds to a condition where the j^{th} flow leaves i^{th} element.

In this paper, the use of an exergy flow graph to determine and represent the main exergetic characteristics for a system with arbitrary structure is described. The exergy flow graph is particularly effective for determining exergy losses in any element of the system or the system as a whole. From the thermodynamic point of view, the value of exergy losses in any element indicates the importance of the element and provides possible ways for improving the overall system's performance. The sum of all element exergy losses within the system provides an excellent objective function for parametric optimization. In addition, the exergy losses are used as a part of the thermoeco- nomical criteria in technical economical analysis of the system. An exergy efficiency model (EEF) and an exergy loss model (EXL) work with the exergy flow graph. Both given below models are based on building and analysis of appropriate matrix of incidences and can be applied for investigation of systems with arbitrary structure.

Outline of EXL model

An EXL model is constructed to determine the exergy losses for a system. This model consists of three main *blocks*.

In the *first block*, the exergy flow graph $E = (A, U)$ and its corresponding matrixes of incidence are built using the rules mentioned in (2).

In the *second block*, the exergy flow associated with each connection on graph $E = (A, U)$ is determined. An important observation is that while considering thermal power and refrigeration systems, there are four main types of exergy flow [3] associated with mass flow, heat flow, work, and fuel flow. Specific mass exergies of these four types and full exergy flow rate can be calculated using equations given in [3]. Then, the sums E_i^{in}, E_i^{out} of exergy flows E_j are formed corresponding to those at the inlet and outlet from i^{th} element of system. In the matrix of incidence element "+1" in the i^{th} line and j^{th} column shows that E_j flow is inlet for i^{th} element of system, "–1" – outlet.

In the *third block*, of the exergy loss model, the exergy losses associated with the i^{th} element, the degree of thermodynamic perfection of the i^{th} element, and the entire system exergy loss are calculated using eqs. (3)-(5). Exergy losses in the i^{th} element of the system are determined using eq. (3):

$$\Pi_i \quad E_i^{\text{in}} \quad E_i^{\text{out}} \tag{3}$$

where Π_i is the exergy loss associated with element i. The degree of thermodynamic perfection of the i^{th} element is found using eq. (4):

$$\nu_i \quad \frac{E_i^{\text{out}}}{E_i^{\text{in}}} \quad 1 \quad \frac{\Pi_i}{E_i^{\text{in}}} \tag{4}$$

where ν_i is the degree of thermodynamic perfection associated with the i^{th} element.

The exergy loss of the entire system is calculated using eq. (5):

$$\Pi_{\Sigma} = \sum_{i=1}^{n} \Pi_i \tag{5}$$

where Π_{Σ} is the exergy loss associated with the entire system.

The EXL model described can be utilized to find degrees of thermodynamic perfection ν_i and exergy losses for individual elements Π_i as well as for the whole system Π_{Σ}.

This approach, however, does not consider the technological aim of the system activities, which is often very important. Such an aspect can be taken into account only with the inclusion of the exergy efficiency of the system. A pipeline can illustrate a simple example of the difference between degree of thermodynamic perfection of an element and its exergetic efficiency. In the best case, the exergy losses in the pipeline are very small (approximately zero) and the degree of thermodynamic perfection is therefore approximately 100%. Notice that this element has no useful efficiency from the thermodynamic point of view and therefore its exergetic efficiency is zero in all cases.

General equation for exergy efficiency of complex systems

The equation, which relates the exergy efficiency of an individual element and the exergy efficiency of the entire system, is stated in eq. (6) [17]:

$$\eta_{\mathrm{ex}}^{\Sigma} = \frac{E_{\Sigma}^{\mathrm{u}}}{E_{\Sigma}^{\mathrm{a}}} = \sum_{i=1}^{m_1} \eta_{\mathrm{ex}}^{i} \beta_i + \sum_{i=1}^{m_2} (\eta_{\mathrm{ex}}^{i} - 1) \beta_i \tag{6}$$

where

$\eta_{\mathrm{ex}}^{i} = E_i^{\mathrm{u}} / E_i^{\mathrm{a}}$ – represents the exergy efficiency of i^{th} element,
$\beta_i = E_i^{\mathrm{a}} / E_{\Sigma}^{\mathrm{a}}$ – represents the influence coefficient of i^{th} element,
E_i^{u}, E_i^{a} – represents the i^{th} element exergy used and available,
E_{Σ}^{u}, E_{Σ}^{a} – represents the total system exergy used and available,
m_1 – represents the number of head elements in the system,
m_2 – represents the number of non-head elements in the system, and
$m = m_1 + m_2$ – represents the total number of elements in the system.

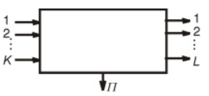
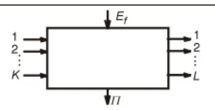
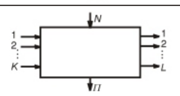
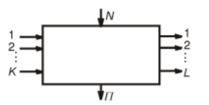
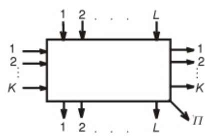
Note that elements that interact with external energy resources are called head elements, otherwise they are called non-head elements.

Although the calculation of the inlet and outlet exergy values of the i^{th} element is independent of the type of the element [17], the calculation of the i^{th} element exergy used and available (E_i^{u} and E_i^{a}) is closely associated with the type of exergy conversion occurring within that particular element. In the analysis of thermal power and refrigeration systems, six different types or groups of elements are usually encountered. Table 1 includes the used E_i^{u} and available E_i^{a} exergy of each common element type. The values are calculated using the same basic formulas. In other energy-intensive systems, such as chemical processing plants, the general types of elements would differ. The EEF model as well as the EXL model requires the building and analysis the exergy flow graph and corresponding matrix of incidence (see example given below). The numbering of nodes on the graph is generally arbitrary. However, a suggestion is offered to ease in organizing certain calculations. Exergy flow associated with elements belonging to the sixth type should be numbered in a special order for E_i^{u} and E_i^{a} where the number of the flow at the exit is a unit larger than that of the flow at the inlet of the element. The numbering of the remaining exergy flows for other types of elements is arbitrary.

Outline of the EEF model

An EEF model is constructed to determine the exergy efficiency for a system. This model consists of four main *blocks*. The *first block* and the *second block* repeat two first blocks of EXL model. In the *third block*, the recognition procedure for the element types and calculation of used and available exergies of the elements by formulas are applied according to tab. 1. In the *fourth block*, exergy efficiency of the i^{th} element

Table 1. Types of elements of thermal-power system

	Name of element	Principal scheme of exergy flows	Used exergy E_i^{u}	Available exergy E_i^{a}
1.	Reservoir, pipeline, pressure regulator, mixer or separator of flows		0	$\sum_{k=1}^{K} E_k^{\mathrm{in}} - \sum_{l=1}^{L} E_j^{\mathrm{out}}$
2.	Electric motor, electric generator		$\sum_{l=1}^{L} E_l^{\mathrm{out}}$	$\sum_{k=1}^{K} E_k^{\mathrm{in}}$
3.	Combustion chamber, nuclear reactor		$\sum_{l=1}^{L} E_l^{\mathrm{out}} - \sum_{k=1}^{K} E_k^{\mathrm{in}}$	E_f – exergy of fuel
4.	Pump, compressor		$\sum_{l=1}^{L} E_l^{\mathrm{out}} - \sum_{k=1}^{K} E_k^{\mathrm{in}}$	N – capacity of pump
5.	Turbine		N – capacity of turbine	$\sum_{k=1}^{K} E_k^{\mathrm{in}} - \sum_{l=1}^{L} E_l^{\mathrm{out}}$
6.	Multiflow recuperative heat-exchanger where K is the number of cold flows and L is the number of hot flows for elements of type 6		$\sum_{k=1}^{K} (E_k^{\mathrm{out}} - E_k^{\mathrm{in}})$	$\sum_{l=1}^{L} (E_l^{\mathrm{in}} - E_l^{\mathrm{out}})$

$\eta^i_{\mathrm{ex}} \quad E^{\mathrm{u}}_i / E^{\mathrm{a}}_i$, the coefficient of influence, $\beta_i \quad E^{\mathrm{a}}_i / E^{\mathrm{a}}_{\Sigma}$, and the exergy efficiency of the whole system are calculated by eq. (6).

Example of thermodynamic analysis of air refrigerator

The models EXL and EEF described are applied to an air refrigerator as shown in fig. 1 in order to determine the exergetic characteristics of the system. The exergy flow graph for this flow sheet is also shown in fig. 1 and the corresponding matrix of incidence is included as fig. 2. Parameters of the various flows (per 1 kg of air) are calculated in [20] and the results are given in tab. 2. In the installation, air with mass flow rate M_{I} = 1 kg/s and

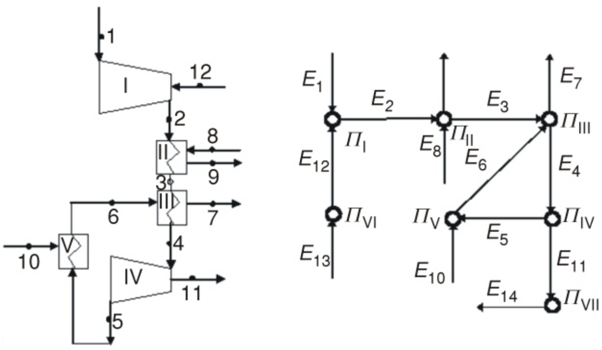


Figure 1. Flowsheet of an air refrigerator with corresponding exergy flow graph. Elements in system include a turbo-compressor (I), intermediate refrigerator (II), regenerative heat exchanger (III), turbo-expander (IV), and a refrigerator (V)

Element	Flow													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
I	+1	–1	0	0	0	0	0	0	0	0	0	+1	0	0
II	0	+1	–1	0	0	0	0	+1	–1	0	0	0	0	0
III	0	0	+1	–1	0	+1	–1	0	0	0	0	0	0	0
IV	0	0	0	+1	–1	0	0	0	0	0	–1	0	0	0
V	0	0	0	0	+1	–1	0	0	0	+1	0	0	0	0
VI	0	0	0	0	0	0	0	0	0	0	0	–1	+1	0
VII	0	0	0	0	0	0	0	0	0	0	0	+1	0	–1

Figure 2. Incidence matrix of the energy flow graph shown in fig. 1 where (0) corresponds to a condition where the j^{th} flow and i^{th} element are not tied, (+1) corresponds to a condition where the j^{th} flow enters the i^{th} element, and (–1) corresponds to a condition where the j^{th} flow leaves the i^{th} element

parameters P_1T_1 enters turbo-compressor I, where it is adiabatically compressed from P_1T_1 to P_2T_2 while consuming 255 kW of power determined using eq. (7):

$$N_{\mathrm{I}} \quad M_{\mathrm{I}}(h_2 \quad h_1) \;\; 1\;(549 \quad 294)[\mathrm{kg/s}][\mathrm{kJ/kg}] \tag{7}$$

The exergy flow rates E associated with this element are listed in tab. 2.

However, the mechanical efficiency η_{mc} of the compressor is 95% and therefore the compressor consumes 268 kW as determined using eq. (8):

$$N_{\mathrm{I}}^{*} \quad \frac{N_{\mathrm{I}}}{\eta_{\mathrm{mc}}} \quad \frac{255}{0.95} \quad 268\ \mathrm{kW} \tag{8}$$

The air then enters the refrigerator II where it is chilled by water (corresponding to flow rates 8 and 9). At the refrigerators exit, the air has been chilled to a condition of P_3 and T_3 as listed in tab. 2. During this heat exchange process, the water traveling through the refrigerator experiences an isobaric increase in temperature from T_8 to T_9. The air then

Table 2. Flow parameters of air refrigerator flowsheet shown in fig. 1

Flow number	T [K]	P [MPa]	h [kJ/kg]	s [kJ/kgK]	E [kW]
0	273.15	0.100	274	6.802	0
1	293	0.098	294	6.867	2.3
2	543	0.620	549	6.921	241.4
3	300	0.610	299	6.356	157.4
4	223	0.590	220	6.067	163.4
5	157	0.109	156	6.205	58.4
6	215	0.103	215	6.536	20.4
7	293	0.098	294	6.867	2.4
8	293	0.300	84.1	0.2962	7.09
9	318	0.300	188.5	0.6377	32.89
10	218	–	–	–	–14.75
11	–	–	–	–	64.0
12	–	–	–	–	255
13	–	–	–	–	268
14	–	–	–	–	59.5

enters the regenerator III, which is a cross flow heat exchanger where heat flows from one air stream to another. The temperature and pressure of the air traveling through the regenerator decreases to condition P_4 and T_4. The chilled air now travels through the turbo-expander where it expands with the removal of capacity determined using eq. (9):

$$N_{IV} = M_I(h_4 - h_5) = 1\ (220 - 156\ )[kg/s][kJ/kg] = 64\ kW \tag{9}$$

The exergy flow rates E associated with this element are listed in tab. 2.

Because the turbo-expander has a mechanical efficiency η_{mt} of 93%, the net power produced by the turbo-expander is determined using eq. (10):

$$N^*_{IV} \quad N_{IV}\eta_{mt} \quad 64 \quad 0.93 \quad 59.5\,kW \tag{10}$$

The air with parameters P_5 and T_5 enters refrigerator V where it maintains a constant temperature within the refrigerated space of T_{10}. Upon exiting the refrigerator V, the air has increased its temperature to T_6 and slightly decreased its pressure to P_6. The last process in this system involves the air entering the regenerator III and removing heat from a hotter air stream. During this process its temperature rises to T_7 while its pressure slightly decreases to P_7. After the air exits the regenerator, it is exhausted from the air refrigerator system. The exergy of each flow is calculated using equations given by Bejan *et al*. [3], where $P_0 = 0.1$ MPa and $T_0 = 273.15$ K, therefore for water $h_0 = 0.1$ kJ/kg, $s_0 = -0.0001$ kJ/kgK, for air $h_0 = 274$ kJ/kg, $s_0 = 6.802$ kJ/kgK. The results are listed for each flow in tab. 2. Here an example is included to demonstrate how the values were calculated for exergy associated with mass flow rate, eq. (11):

$$E_j \quad M_j(e_j) \quad M_j[(h_j \quad h_{j0}) \quad T_0(s_j \quad s_{j0})]$$

$$E_I \quad M_I(e_1) \quad M_I[(h_1 \quad h_{10}) \quad T_0(s_1 \quad s_{10})] \tag{11}$$

$$E_I \quad 1[kg/s]\ \{(294 \quad 274)[kJ/kg] \quad 273.15\,(6.867 \quad 6.802)[K][kJ/kgK]\} \quad 2.3\,kW$$

Table 3 includes a summary of the results. As shown in tab. 3, the largest exergy losses occur in the refrigerator II with a value of 58.2 kW. The exergy losses in the heat exchangers are caused by irreversibility associated with heat transfer across a large temperature difference between the hot side and the cold side flows. The larger the temperature difference, the larger the irreversibility and the exergy loss. Subsequently, the exergy efficiency and degree of thermodynamic perfection both decrease. Another factor that has influence on the exergy efficiency of the heat exchangers is the temperature of the hot side and the cold side flows. The higher the temperature, the less exergy is lost and therefore the higher the exergy efficiency.

Exergy losses in the turbo-expander and turbo-compressor result from the dissipation of expansion (pressure) processes in a real installation. The degree of thermodynamic perfection and exergy efficiency of turbo-expander and turbo-compressor are sufficiently high. Usually, the larger the difference between the average parameters of the

Table 3. Thermodynamic characteristics of air refrigerator shown in fig. 1

Element	Sum of exergy flow rates at inlet to element E_i^{in} [kW]	Sum of exergy flow rates at outlet from element E_i^{out} [kW]	Rates of exergy losses in element Π_i [kW]	Flow rate of used exergy E_i^{u} [kW]	Flow rate of available exergy E_i^{a} [kW]	Coefficient of influence β_i	Exergy efficiency η_{ex}^{i}	Degree of thermodynamic perfection ν_i
Turbo- -compressor I	257.4	241.4	16.0	239	255	0.957	0.937	0.937
Refrigerator II	248.5	190.3	58.2	25.8	84	0.313	0.307	0.766
Regenerator III	177.8	165.8	12.0	6.0	18.0	0.0672	0.333	0.933
Expander IV	163.4	122.4	41.0	64.0	105	0.392	0.609	0.749
Refrigerator V	43.7	20.4	23.3	14.75	38	0.142	0.388	0.467
Drive of turbo- -compressor VI	268	255	13.0	255	268	1	0.951	0.951
Drive of expander VII	64	59.5	4.5	59.5	64	0.238	0.929	0.929

working fluid and the environment, the smaller the exergy losses. Exergy losses in the drives of turbo-expander and turbo-compressor are the result of dissipation (mechanical friction). Based on the values listed in tab. 3, the sum of inlet and outlet exergies are determined using eqs. (12) and (13). The available and used exergies are determined using eqs. (14) and (15):

$$E_{\Sigma}^{\text{in}} \quad E_1 \quad E_8 \quad E_{10} \quad E_{13} \quad 263 \text{ kW} \tag{12}$$

$$E_{\Sigma}^{\text{out}} \quad E_7 \quad E_9 \quad E_{14} \quad 95 \text{ kW} \tag{13}$$

$$E_{\Sigma}^{\text{a}} \quad E_{13} \quad 268 \text{ kW} \tag{14}$$

$$E_{\Sigma}^{\text{u}} \quad |E_{10}| \quad E_{14} \quad 74.25 \tag{15}$$

For the entire system, the exergy loss is determined using eq. (16), the exergy efficiency is determined in eq. (17), and the degree of thermodynamic perfection is calculated using eq. (18):

$$\Pi_{\Sigma} \quad \sum_{i\ 1}^{7} \Pi_i \quad 168 \text{ kW} \tag{16}$$

$$\eta_{\mathrm{ex}}^{\Sigma} \quad \frac{E_{\Sigma}^{\mathrm{u}}}{E_{\Sigma}^{\mathrm{a}}} \quad \frac{74.25}{268} \quad 0.277 \qquad (17)$$

$$\nu_{\Sigma} \quad \frac{E_{\Sigma}^{\mathrm{out}}}{E_{\Sigma}^{\mathrm{in}}} \quad \frac{95}{263} \quad 0.361 \qquad (18)$$

It is of interest and importance to note that the exergy efficiency as well as the degree of thermodynamic perfection of the whole system is less than the same characteristics for every element of the system. This is due to the mutual interaction influence among the element in the system.

Conclusions

An innovative method of structural exergy analysis is described. This general approach to thermodynamic analysis of systems is based on special properties of exergy-topological models, which can be constructed for all energy-intensive systems. A novel calculation method of exergy efficiency is based on a general equation for arbitrary structure systems and on an exergy flow graph. Exergy-topological models are invariant of the technological aim and structure of the system. The models can be applied to the analysis and evaluation of energy intensive systems in different branches of industry. The illustrative example given demonstrates the applicability of the proposed method to the thermodynamic analysis of an air refrigerator.

Nomenclature

A – multitude of nodes, [–]
E – exergy flow rate, [W]
e – specific exergy, [J/kg]
h – specific enthalpy, [J/kg]
M – mass flow rate, [kg/s]
m_1 – the number of head elements of the system, [–]
m_2 – the number of other (not head) elements of the system, [–]
m – the total number of elements of the system, [–]
N – capacity, [W]
P – pressure, [Pa]
s – specific entropy, [$\mathrm{Jkg^{-1}K^{-1}}$]
T – temperature, [K]
U – arcs multitude, [–]

Greek letters

β – influence coefficient, [–]
Γ – multivalued display of multitude A into itself, [–]
η – efficiency, [–]
ν – degree of thermodynamic perfection, [–]

Π – rate of exergy losses, [W]

Subscripts and superscripts

a – available
ex – exergy
i – number of element (node)
in – inlet of element
j – number of flow
k, l – number of element (node)
out – outlet of element
u – used
Σ – for system on the whole
0 – point of equilibrium with the environment

References

[1] Moran, M., Engineering Thermodynamics, CRC Press, Boca Raton, FL, USA, 1998
[2] Bejan, A., Advanced Engineering Thermodynamics, John Wiley & Sons, New York, USA, 1997
[3] Bejan, A., Tsatsaronis, G., Moran, M., Thermal Design and Optimization, John Wiley & Sons, New York, USA, 1996
[4] Cornelissen, R., Boerema, C., Exergy Scan, the New Method for Cost Effective Fuel Saving, *Proceedings*, International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems, Istanbul, Turkey, 2001, pp. 725-733
[5] Falsetta, M., Sciubba, E., Exergy-Based Analysis of the Start up Transient of a Combined Cycle Plant, *Proceedings*, International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems, Nancy, France, 1998, pp. 775-787
[6] Hirs, G., Exergy Loses: a Basis for Energy Taxing, *Proceedings*, NATO-ASI Workshop on Thermodynamic and Optimization of Complex Energy Systems, Constance, Romania, 1998, pp. 195-208
[7] Sciubba, E., Exergy as a Measure of Environmental Impact, *Proceedings*, Advances in Energy Studies, Nashville, Tenn., USA, 1999, pp. 121-125
[8] Finnveden, G., Ostlund, P., Exergies of Natural Resources in the Life Cycle Assessment and other Applications, *Energy, 22* (1997), 9, pp. 923-932
[9] Gaggioli, R., Richardson, D., Bowman, A., Paulus, D., Available Energy: Part 1, Gibbs Revisited, & Part 2, Gibbs Extended, *Proceedings*, Advances in Energy Studies, Nashville, Tenn., USA, 1999, pp. 232-239
[10] Wall, G., Conditions and Tools in the Design of Energy Conversion and Management Systems of Sustainable Society, *Proceedings*, International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems, Tokyo, 1999, pp. 125-133
[11] Graveland, G., Exergy Analysis: An Efficient Tool for Process Optimization and Understanding, *Comp. Chem. Eng., 22* (1998), 4, pp. 545-552
[12] Huang, F., Naumovicz, T., Energy as well as Exergy Evaluation of Overall Performance of Combined Gas-Steam Power Plants, *Proceedings*, International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems, Twente, The Netherlands, 2000, pp. 435-437

[13] Oh, S., Pang, H., Yong, K., Exergy Analysis of a Gas Turbine Cogeneration Systems, *Journal of Gas Turbine and Power, 118* (1996), 4, pp. 253-260
[14] Wu, C., Nikulshin, V., Method of Thermoeconomical Optimization of Energy Intensive Systems with Linear Structure on Graphs, *International Journal of Energy Research, 24* (2000), 1, pp. 615-623
[15] Nikulshin, V., Wu, C., Thermodynamic Analysis of Energy Intensive Systems on Exergy Topological Models, *Proceedings*, 12th International Simposium on Transport Phenomena, Istanbul, Turkey, 2000, pp. 433-438
[16] Nikulshin, V., Wu, C., Thermodynamic Analysis of Energy Intensive Systems on Exergy – Topological Models, *Exergy, 10* (2001), pp. 1-10
[17] Nikulshin, V., Wu, C., Nikulshina, V., Exergy Efficiency Calculation of Energy Intensive Systems by Graphs, *Proceedings*, International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems, Istanbul, Turkey, 2001, pp. 107- 114
[18] Nikulshin, V., Andreev, L., Exergy Efficiency of Complex Systems, *Proceedings*, International Conference of Ocean Technology and Energy, Imari, Japan, 1999, pp. 162-171
[19] Nikulshin, V., Wu, C., Method of Thermodynamic Analysis and Optimisation of Energy Intensive Systems on Exergy Flow Graphs, *Proceedings*, International Conference on Power and Energy Systems, Las Vegas, NV, USA, 1999, pp. 489-491
[20] Andreev, L., Nikulshin, V., Thermodynamic Analysis of Power-Technological Systems on Computer (in Russian), The Centre of Higher Education and Methods of Ukraine, Kiev, 1992
[21] Harary, F., Graph Theory, Narosa Publishing Housen, New Deli,1995

Authors' addresses:

V. Nikulshin
Odessa National Polytechnic University
1, Ave. Shevchenko
65044 Odessa, Ukraine

M. Bailey
U. S. Military Academy
West Point, New York 10996
USA

V. Nikulshina
Odessa State Academy of Refrigeration
1/3, Dvoryanskaya St.
65100 Odessa, Ukraine

Corresponding author (V. Nikulshin):
E-mail: vnikul@paco.net

Paper submitted: December 2, 2004
Paper revised: February 4, 2005
Paper accepted: February 13, 2006