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Optimization of system for thermal treatment of chlorine water

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ABSTRACT

In the design and operation of energy intensive systems the problem of improving the efficiency is very important. The main way for solving this problem is optimization. This paper describes the general approach for thermoeconomical optimization systems with a linear structure. The suggested method is based on building and analysis of special graphs of thermoeconomical expenditure. The method is illustrated by an example system optimization for thermal treatment of chlorine water.

Keywords: Optimization; Linear systems; Graphs; Thermoeconomic; Chlorine water

1. Introduction

Processes that take place in complex energy intensive systems are characterized by mutual transformation of quantitatively different power resources. The fast growth and development of modern technologies requests thermodynamic analysis and optimization of such systems, based on the combined application of both laws of thermodynamics, and demands an exergy approach [1,2]. Exergetic methods are universal and make it possible to estimate the energy fluxes and to develop energy balances for every element of the system using a common criterion of efficiency. Therefore, the exergetic methods are meaningful in analysis and calculations.

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 exergetic methods have been published [3–7].

The above referenced papers, as well as the author's earlier investigations [8–13] show that one of the most effective mathematical methods used for exergetic analysis and optimization is the method of graph theory [14,15]. The benefit of graph models can also be demonstrated by its flexibility and its wide varieties of possible applications.

Possible exergy topological methods include the sole use or combination of exergy flow graphs, exergy loss graphs, and thermoeconomical graphs [3–7].

Systems with linear structure are often used in energy technology as well as in other branches of industry. For that reason it is necessary to study the problem of linear structures systems optimization separately from the systems of arbitrary structure.

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2. Method optimization of linear system

First, let us consider a homogeneous system that contains **n** different elements of one type (as shown in Fig. 1).

In this system one flow h_j, $j = 1$ interacts successively with flows C_i, $i = 1,2, \ldots n$.

In the problem of optimal synthesis, this can be reformulated in such a way:

It is necessary to distribute the multitude of flows

$$C = \{C_1, C_2, \ldots C_i, \ldots, C_n\}$$

along the flow h_j ($j = 1$) and in result of interaction of which parameters of flow in outlet of system will be in interval of required constrains and thermoeconomical criteria will be minimized

$$\sum_i \sum_j Z_{ij} = Z_\Sigma^{\min} \quad (1)$$

where Z_{ij} -thermoeconomical expenditure at i-element ($j = 1$).

For solving this type of a problem, it is necessary to build the graph of thermoeconomical expenditure as it was shown in [8]. In our case this graph will be a tree $Z = (N,D)$, the multitude of nodes N displays the possibility of distribution of flows in the system, the multitude of arcs D, displays the possible meanings of thermoeconomical expenditures.

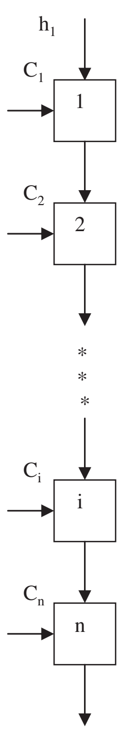

Fig. 1. Linear system.

The governing equations which are representing these levels are:

$$N_p = \left\{C_1^{(p)}, C_2^{(p)}, \ldots, C_{i_p}^{(p)}, \ldots, C_{[n-(p-1)]}^{(p)}\right\} \quad (2)$$

$$p = 1, 2, \ldots, k; i_p = 1, 2, \ldots, [n - (p - 1)]$$

where

$$N_p \subset C, p = 1, 2, \ldots, k,$$

$$p = 0 \Rightarrow |N_0| = 1$$

$$p = 1 \Rightarrow |N_p| = |C|, C - N_p = \varnothing \quad (3)$$

$$1 \le p \le k \Rightarrow |N_p| \le |C|$$

$$\forall\left(C_{i_{p-1}}^{(p-1)}, C_{i_p}^{(p)}\right) \in D \Rightarrow \left(C_{i_{p-1}}^{(p-1)}, C_{i_p}^{(p)}\right) = Z_{i_p}^{(p)} \quad (4)$$

$$\forall\left(C_{i_{p-1}}^{(p-1)}, C_{i_p}^{(p)}\right) \notin D \Rightarrow \left(C_{i_{p-1}}^{(p-1)}, C_{i_p}^{(p)}\right) = \infty$$

where symbol ∞ shows that arcs of this type are absent.

The flow h_j in graph $Z(N,D)$ is described as node $C_0^{(0)}$. Then for obtaining conditions (1) it is necessary to find an optimal way.

$$\bar{C} = \left(C_0^{(0)}, C_1^{(1)}, \ldots, C_{i_p}^{(p)}, \ldots, C_{[n-(p-1)]}^{(k)}\right)\bar{C} \subset N, \quad (5)$$

so that (see Fig. 2)

$$\sum_{i_p} \sum_p Z_{i_p}^{(p)} = Z_\Sigma^{\min} \quad (6)$$

The algorithm of Belmann-Kalaba is usually used for seeking the optimal way in graphs without contours. This algorithm is based on the matrix of thermoeconomical expenditure [8,9].

In our case the graph of thermoeconomical expenditure is successive:

$$\Gamma_p N_p = N_{p+1} \tag{7}$$

where Γ_p is the display of set N_p, and condition of Eq. (4) will be valid for elements of matrix which are located in the intersection of columns $C_{i_p}^{(p)}$ and lines $C_{i_{p-1}}^{(p-1)}, p = 1, 2, \ldots, k;\ i_p = 1, 2, \ldots, [n-(p-1)]$. This feature of graph of thermoeconomical expenditure allows one to simplify the matrix of expenditure and to reduce the number of analyzed variants in n times [8,9].

Based on the features of the thermoeconomical expenditure graph, we recommend the algorithm of searching an optimal variant be used.

Each step of seeking an optimal variant is successively compared with thermoeconomical expenditure $Z_{i_p}^{(p)}$ and $Z_{\min}^{(p)}$. In result, the flow corresponding to Eq. (6) can be found. Then applying the procedure of seeking $Z_{\min}^{(p)}$ to all K steps, we will find the optimal flow distribution which corresponds to the condition in Eq. (1).

In case of inhomogeneous linear systems optimization, the main idea of this approach will remain.

Since inhomogeneous elements are able to change the different characteristics of flow h_j, it is necessary to consider not only the pth-step but also the previous steps of the system's optimization. Consequently the method of dynamic programming has to be changed to the branch and bound method. With this approach at each step we seek and then save expenditure $Z_{\Sigma}^{(p)\min}$, where $Z_{\Sigma}^{(p)}$ is the sum of thermoeconomical expenditure for all p steps of the considered variant. Then expenditure $Z_{\Sigma}^{(p)\min}$ will be compared with the analogous sums for the previous steps $(p-1), (p-2), \ldots, 1$.

Then the variant corresponding to the following equation has to be developed

$$Z_{\Sigma}^{\min} = \min\left[Z_{\Sigma}^{(l)\min}\right], l = 1, 2, \ldots, p \tag{8}$$

Then elements for the next step of optimization have to be taken from the multitude N_{p+1}, which corresponds to Eq. (7).

3. Optimal synthesis of chlorine water refrigeration

The systems of chlorine water refrigeration usually have a linear structure. It is illustrated in Fig. 1. In this case the flow h_1 will display the flow of refrigerated chlorine water and C is the set of flows which refrigerate the flow h_1. The set of flows C includes flows of industrial water and cooled water. If industrial water is used, the surface of heat exchangers and appropriate expenditures will be bigger than in the case of using cooled water. But using cooled water requires the additional expenditures for its cooling. So the question is to find the variant of the system of chlorine water refrigeration with minimum expenditure:

$$Z_{\Sigma} = \sum_{i=1}^{n} Z_i^{\min} \tag{9}$$

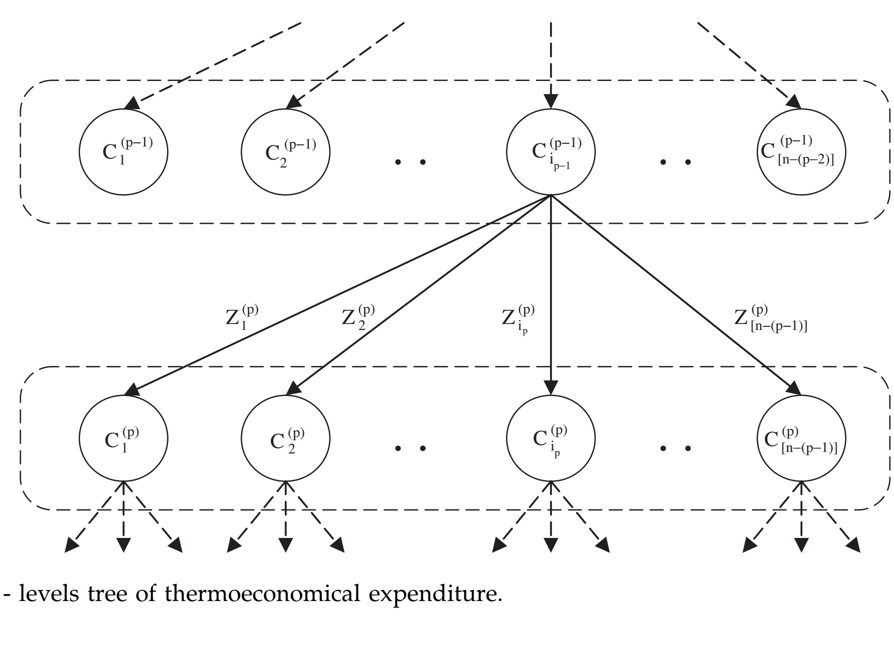

Fig. 2. (P-1) and P - levels tree of thermoeconomical expenditure.

$$Z_i^{\min} = \min\{(Z_i^A + Z_i^{iw}), (Z_i^A + Z_i^{cw})\} \quad (10)$$

where:

Z_i^A is the yearly investments cost (for surface, repairing, salary of personnel etc.) for heat exchanger i,

Z_i^{iw} is the yearly expenditure for industrial water,

Z_i^{cw} is the yearly expenditure for cooled water.

$$Z_i^{cw} = P_i^{cw} E_i^{cw} \tau \quad (11)$$

where:

P_i^{cw} is the price of one kJ cooled water.

E_i^{cw} is the exergy of cooled water which can be calculated as the exergy of heat flow entering into heat exchanger i,

τ is the period work of the system during a year.

$$Z_i^{iw} = P_i^{iw} m_i^{iw} \tau \quad (12)$$

Here:

P_i^{iw} is the price of one kilogram of industrial water (as the differences between the parameters of industrial water and environment are very little we can assume that the exergy of industrial water is equal to zero) for heat exchanger i.

m_i^{iw} is the mass flow of industrial water for heat exchanger i.

As an example, the typical line of chlorine production was taken (the mass flow of chlorine is 2.53 kg/s) with mass flow of chlorine water, 10.9 kg/s. The working time during a year is = 7,200 h. The temperature of chlorine water at the inlet of the system is 50° C and the required temperature at the outlet of the system is 15°C. The heat exchangers for such scheme are titanium refrigerators the surface of each is 60 m^2 with the coefficient of heat transfer being 700 W/(m^2 K). The initial temperature of the industrial water is 20°C. The initial temperature of cooled water is 5°C. The yearly investments cost for the heat exchanger is 0.0666 USD for one square meter of the surface. The price of exergy of cooled water is 0.0038 USD/MJ and the price of industrial water is 0.065×10^{-6} USD/kg.

Application of the procedure described above for optimization of this system gives the tree of solution as shown in Fig. 3. The left branch of the tree displays variants of using cooled water, and the right branch-industrial water. Each level of the tree (excluding level zero) has two nodes with the appropriate temperature of chlorine water and thermoeconomical expenditure. For further developing of tree on each level taken the node with a minimum of Z, as it was described above.

It is seen that on the first three levels, is chosen the variant of using industrial water and only on the last one–cooled water. So the optimal system of chlorine water refrigeration will include three heat

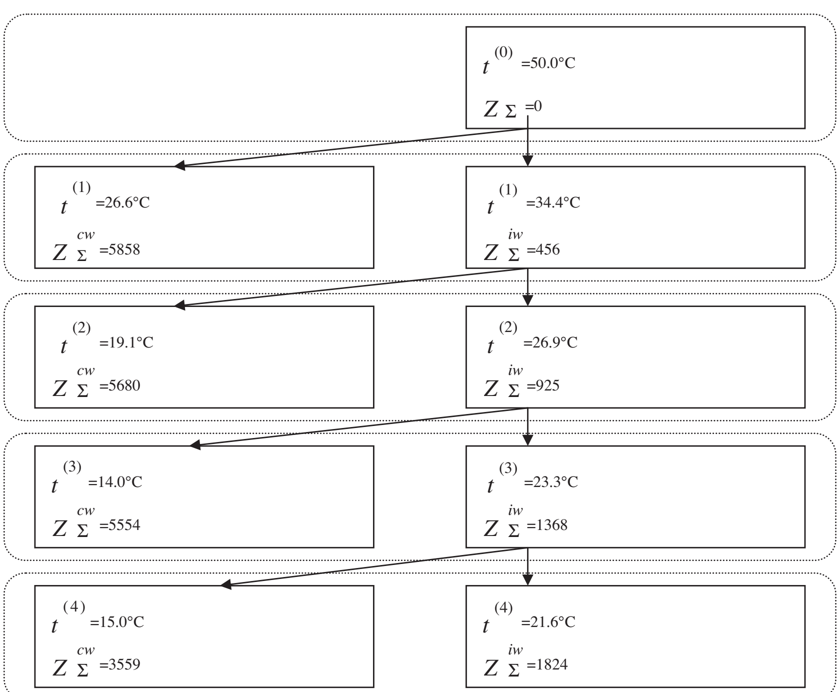

Fig. 3. Tree of possible thermoeconomical expenditure the system of chlorine water refrigeration.

exchangers with industrial water and one with cooled water.

The optimal meaning of thermoeconomical expenditure for this system is 3,559 USD per year.

4. Conclusion

The problem of optimization linear systems has to be solved separately from the problem of optimization of systems with arbitrary structure. On the basis of the features of linear systems it is possible to build an effective procedure of optimization. The suggested method is based on developing and analyses of the graph of thermoeconomical expenditure. It allows one to find the optimal variant for homogeneous systems as well as for systems with different tips of elements. The method is illustrated by an example of chlorine water refrigeration system optimization.

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