THERMOECONOMICAL OPTIMIZATION OF HEAT SUPPLY SYSTEM FOR COTTAGE COMPLEX

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Abstract: 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 optimization. This paper describes a general approach for thermoeconomical optimization of heat supply system (HSS) for cottage complex. The suggested method is based on the construction and analysis of a thermoeconomical expenditure graph. The method is illustrated with on
example of optimization of real heating system for cottage complex with four buildings.

Keywords: thermoeconomics, optimization, graphs, heat supply system

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1. 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 (Bejan et al., 1996, Sciubba et al., 1998).

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 exergetic methods have been published (see for example Sciubba et al., 2001, Erlach et al., 2000, Casarosa et al., 2001, Cornelissen et al., 2000) The above referenced papers, as well as the author's earlier investigations (Nikulshin et al.,1999-2006) show that one of the most effective mathematical methods used for exergetic analysis and optimization is the method of graph theory. The benefit of graph models can also be demonstrated by its flexibility and 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 (Nikulshin et al., 1999-2006)

The thermoeconomical approach allows to retain all advantages of exergy method and simultaneously estimate the investment and other monetary costs of a system.

In this Paper is developed the method of thermoeconomical optimization of a heat supply system for cottage complex.

2. GRAPH OF THERMOECONOMICAL EXPENDITURE FOR HEAT SUPPLY SYSTEM

Past optimization research of actual energy intensive systems was successfully conducted using exergy flow graphs (Nikulshin et al., 2000, 2001). However, for considering the rather broad class of systems with pair interplay of flow , was suggested a graph of thermoeconomical expenditure

(Nikulshin et al., 2001, 2002).

This type of graph represents one kind of possible exergy-topological models.

In application to heat supply system (HSS) it is a bipartite graph $Z = (C \cup H, \Gamma_n) = (C \cup H, D)$. The graph consists of the set of nodes $C \cup H$ corresponding to the multitude of heat sources $H = \{h_1, h_2, \dots, h_i, \dots, h_m\}$ and multitude of heat consumers $C = \{c_1, c_2, \dots, c_i, \dots, c_n\}$, as well as the set of arcs $D = \{h_i, c_j\}$, $i=1,2\dots, m; j=1,2\dots, n;$ which represent the possible distribution of thermoeconomical expenditure in the HSS. The graph of thermoeconomical expenditure is the simple graph of a view:

$$H \cap C = \varnothing \tag{1}$$
$$(\forall h_i \in H)\Gamma_n h_i \in C \tag{2}$$
$$(\forall c_i \in C)\Gamma_n c_j = \varnothing \tag{3}$$

Than every *i, j*- pair (h_i, c_j) from sets $H = \{h_1, h_2, \dots, h_i, \dots, h_m\}$ and $C = \{c_1, c_2, \dots, c_j, \dots, c_n\}$ will be uniquely characterized with appropriate thermoeconomical expenditure Z_{ij}.

The problem of optimal, thermoeconomical synthesizing can be solved by minimizing the sum shown in Eq. (4)

$$Z_{\Sigma}^{\min} = \min \sum_i \sum_j Z_{ij} \tag{4}$$

Lets assume that the procedure of its optimization has s-steps. Also, lets take intermediate p-step $(1 \le p \le s)$ and assume that on the p-step the optimal pairs of $(m-m_p)$ heat sources h_i, $(m > m_p > 0)$ and $(n-n_p)$ of heat consumers c_j, $(n > n_p > 0)$, are found. Then in the result of minimizing the sum given in Eq. (4) on every p-step, the optimal system will be obtained (Nikulshin et al., 2002).

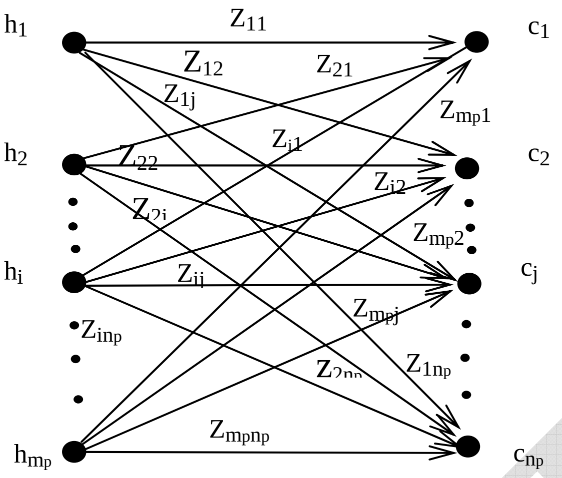

Figure 1- Bipartite graph of thermoeconomical expenditure for a *p*-step.

$$\begin{array}{cccccc} Z_{11} & Z_{12} & \ldots & Z_{1j} & \ldots & Z_{1np} \\ Z_{21} & Z_{22} & \ldots & Z_{2j} & \ldots & Z_{2np} \\ \ldots & \ldots & & \ldots & & \ldots \\ Z_{i1} & Z_{i2} & \ldots & Z_{ij} & \ldots & Z_{inp} \\ \ldots & \ldots & & \ldots & & \ldots \\ Z_{mp1} & Z_{mp2} & \ldots & Z_{mpj} & \ldots & Z_{mpnp} \end{array}$$

Figure 2- Matrix of graph in Fig.1.

In order to optimize a p-step, the graph of thermoeconomical expenditure for a *p*-step $\bar{Z} = (\bar{H} \cup \bar{C}, \bar{\Gamma}_n) = (\bar{H} \cup \bar{C}, \bar{D})$ shown in Fig.1 will be considered.

Here

$$\begin{array}{l} H \cap \bar{C} = \varnothing \\ (\forall h_i \in \bar{H})\ \bar{\Gamma}_n h_i \in \bar{C} \\ (\forall c_j \in \bar{C})\ \bar{\Gamma}_n c_j = \varnothing \\ H = \{h_1, h_2..., h_i,..., h_{mp}\} \\ C = \{c_1, c_2..., c_j,..., c_{np}\} \end{array} \tag{5}$$

The set of arcs of the graph $\bar{Z} = (\bar{H} \cup \bar{C}, \bar{D})$

$\bar{D} = \{h_i, c_j\},\ i=1,2, ..., m_p; j=1,2, ..., n_p$

is defined as:

$$(h_i, c_j) \in \bar{D} \Rightarrow (h_i, c_j) = Z_{ij} \tag{6}$$

Set $\bar{D}$ can be divided into two subsets, $\bar{D}_1 \cup \bar{D}_2 = \bar{D}$ and $\bar{D}_1 \cap \bar{D}_2 = \varnothing$ for which conditions given in Eqs. (7) and (8) are satisfied.

$$\forall (h_i, c_j) \in \bar{D}_1 \Rightarrow Z_{ij} \neq \infty \tag{7}$$

$$\forall (h_i, c_j) \in \bar{D}_2 \Rightarrow Z_{ij} = \infty \tag{8}$$

The version with $D_2 = \varnothing$ is also possible but generally $D_2 \neq \varnothing$.

For finding the coupling that will minimize Eq. (4), a minimum bearing (Nikulshin et al., 2002) of simple graph $\bar{Z} = (\bar{H} \cup \bar{C}, \bar{D})$ is found which corresponds to a unique matrix of thermoeconomical expenditure, MZ_{ij} of the size $m_p \times n_p$ (shown in Fig.2).

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The minimization problem is reduced to finding row vectors $Z_i = \{Z_{i1}, Z_{i2}, ..., Z_{imp}\}$ and vectors of columns $Z_j = \{Z_{j1}, Z_{j2}, ..., Z_{jmp}\}$, that meet the condition given in Eq. (4).

By transforming the matrix MZ_{ij}, the elements under conditions Eq. (7) are eliminated from consideration.

The outcomes are elements Z_{ij}, which are optimal for the given p-step

The algorithm of the solution does not vary as the step is transitioned to $p+1$ and to $p = s$.

After each step, the sizes of a matrix MZ_{ij} will be diminished and at p = s the matrix becomes equal to zero point.

Step by step algorithm of this procedure is given in (Nikulshin et al., 2002)

3. OPTIMAL SYNTHESIS OF REAL HEAT SUPPLY SYSTEM FOR COTTEGE COMPLEX

It is necessary to design the optimal heat supply system for cottage complex with four buildings. The main characteristics of these buildings are given in table 1.

Table 1.Main characteristics of buildings

Number of building	Number of stores	Total square m^2	Number of residents
1	2	256	9
2	3	642	22
3	3	642	22
4	3	742	25

Building 1 was built and occupied 5 years ago.

Buildings 2-4 are in different stages of construction (end of building and occupation is planed in the next year).

All four buildings are located in corners of a square with a side 50 meters.

Heat supply of a building 1 is organized by a boiler non-condense type KV-1 (see Table 2).

For developed heating systems were considered two main options:

1. Using the cheaper boilers KV non-condense type (see Table 2), but with low energy efficiency (85%).
2. Using more expensive modern boilers KC - condense type (see Table 3), but with a rather high energy efficiency (95%).

Besides that for both options were considered the possibility not only to create individual heating system (one boiler -one building) but also to create a district heating y system (one boiler-few buildings).

In accordance with a roles given in (Nikulshin et al., 2001, 2002) can be built the graph of thermoeconomical expenditure in designed HSS (see Fig.3.).

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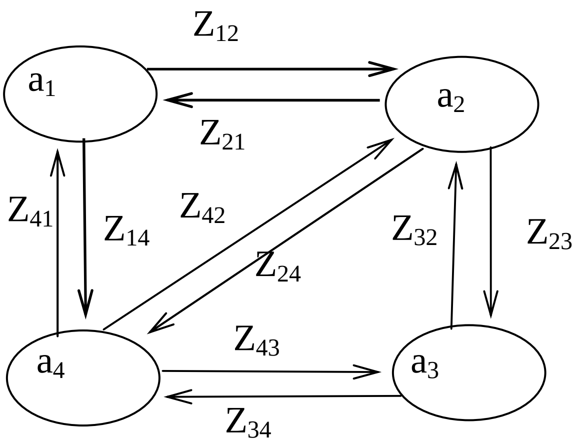

Figure 3 - Graph of possible thermoeconomical expenditure in designed HSS.

Here the nodes a_1 - a_4 of graph of thermoeconomical expenditure corresponds to the buildings 1-4 and arcs (a_i, a_j), $i=1,2,3,4;$ $j=1,2,3,4$ corresponds to appropriate parts of heating grid.

For simplification of optimization procedure it will be helpful to include in the possible thermoeconomical expenditure Z_{ij} , $i=1,2,3,4;$ $j=1,2,3,4$ not only thermoeconomical expenditure of a heating grid but also a part of thermoeconomical expenditure (proportionally to heat capacity) of a boiler.

It is clear that for the variant of individual heating system the heating network between the building will be absent.

In general case $Z_{ij} \neq Z_{ji}$, as a result the different heating demands in different buildings (in analyzed case only $Z_{23} = Z_{32}$).

Now it is possible to build the graph of thermoeconomical expenditure (see Fig. 4) in accordance with Eqs. (1)-(3) given above.

The multitude of heat sources $H = \{h_1, h_2..., h_i,..., h_m\}$, $m=10$ corresponds to the possible variants of used boilers (with appropriate part of heating network for district heating variant) and multitude $C = \{c_1, c_2..., c_i,..., c_n\}$, $n=4$ corresponds to of heat consumers (buildings 1-4).

Table 2.Main characteristics of non-condense boilers (type KV)

Heat capacity, kW	345	735	850	1520	2530
Price, USD	17250	34000	35840	62660	96500
Corresponding node of graph	h_{11}	h_{21}	h_{31}	h_{41}	h_{51}

Table 3.Main characteristics of condense boilers (type KC)

Heat capacity, kW	360	725	875	1640	2620
Price, USD	36000	41160	1530	51000	128660
Corresponding node of graph	h_{12}	h_{22}	h_{32}	h_{42}	h_{52}

A fuel for boilers is natural gas (Price 0.0593 USD/m^3, Q=35 MJ/ m^3).

For calculations of heat demands were taken the follow integrated characteristics:

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- demand for heating 1.2 kW/ m^2 for building 1(old design) and 1.1 kW/ m^2 for buildings 2-4 (modern design). The heating period October, 15 - April, 15.
- demand for heat water supply (all over the year) is120 liters per person per day (0.4 kW per person)
- speed of water in a pipes between buildings 1.5m/s

Investment cost in heating network (in pipelines) were calculated by Eq. (9)

$$K_c=(20+210)L, \quad USD \tag{9}$$

here d-diameter and L- length of pipeline.

Refund period (under request of a customer) is 5 years.

Thermoeconomical expenditures were calculated by the method given in (Nikulshin et al., 2002).

Let's describe the first step (the other steps are analogously) of suggested approach on example of calculation of thermoeconomical expenditure for building 2.

In accordance with a heat demand (see Tabl.4) of a building 2 (node c_2 of graph in fig.4) it is possible to create a heating system from all heat sources (except h_{11}, h_{12}, which have the less of requested heat capacity). For this reason there are eight arcs, connected with a node c_2 and it is necessary to calculate the thermoeconomical expenditures on these arcs.

Table 4. Heat demand of consumers

Consumer	Building 1	Building 2	Building 3	Building 4
Heat demand , kW	310	715	715	826
Corresponding node of graph in Fig.4	c_1	c_2	c_3	c_4

Arc $(h_{21}- c_2)$. Here a boiler is located in a building 2 so expenditures for heating network (pipe lines) between building will absent and the thermoeconomical expenditures will contain two parts "year price" of natural gas Z_{21}^{gas} and "year investment and operation cost" of boiler Z_{21}^{b} .

$$Z_{21}^{\Sigma} = Z_{21}^{gas} + Z_{21}^{b} = 28970 \ USD/year$$

Arc $(h_{22}- c_2)$- analogously to arc $(h_{21}- c_2)$.

$$Z_{22}^{\Sigma} = Z_{22}^{gas} + Z_{22}^{b} = 29070 \ USD/year$$

Arcs $(h_{31}- c_2)$ and $(h_{32}- c_2)$. Here a heat capacity of each of both boilers are bigger then requested 715 kW but they are not enough to cover some additional demand, so expenditures Z_{31}^{Σ} and Z_{32}^{Σ} will be for sure bigger then the same characteristics for previous variants so it is possible to exclude this option from further consideration.

Arc $(h_{41}- c_2)$. As a boiler can be also placed in the building 3 it is necessary to take into account expenditures of a pipe line network between buildings Z_{41}^{p}.

So now the total thermoeconomical expenditure will contain three parts:

$$Z_{41}^{\Sigma} = Z_{41}^{gas} + Z_{41}^{b} + Z_{41}^{p} = 28680 \ USD/year$$

Arc $(h_{42}- c_2)$-analogously to arc $(h_{41}- c_2)$.

$$Z_{42}^{\Sigma} = Z_{42}^{gas} + Z_{42}^{b} + Z_{42}^{p} = 27600 \ USD/year$$

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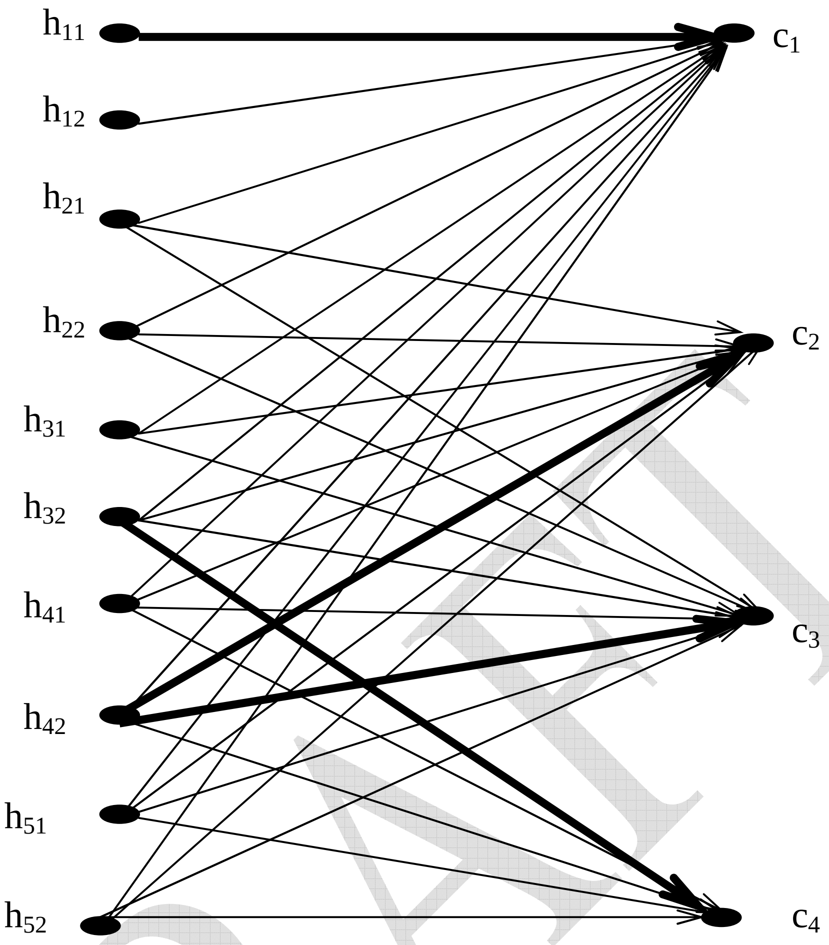

Figure 4 - A bipartite graph of possible thermoeconomical expenditure in HSS.

Arcs (h_{51}- c_2) and (h_{52}- c_2) analogously to arcs (h_{41}- c_2) и (h_{42}- c_2), but a boiler can be placed in a building 4, were is located the maximum heat demand in all cottage complex.

$Z_{51}^{\Sigma}=Z_{51}^{gas} + Z_{51}^{b} + Z_{51}^{p}= 28450$ *USD/year*

$Z_{52}^{\Sigma} = Z_{52}^{gas} + Z_{52}^{b} + Z_{52}^{p} = 27700$ *USD/year*

It is easy to see that the minimum meaning of Z_{ij}^{Σ} is Z_{42}^{Σ}, which (it showed the optimization procedure) was also taken in the final variant of total optimal system.

The nodes of graph corresponding to optimal variant of heating supply system are marked by a bold lines in Fig.4.

Optimal variant provides:

Building 1 - retain the existing heating system from a boiler h_{11} -see table 4.2. (because the new boiler will not be refunded during 5 years).

$Z_{11}^{\Sigma}(1) =9600$ *USD/year* - in practices only cost of natural gas.

Building 2 and building 3 have a common heat supply system from one boiler h_{42} -see table 4.3. This boiler locates in the building 3 . For building 2

$Z_{42}^{\Sigma} (2) = 27600$ *USD/year*

For building 3

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$Z_{42}^{\Sigma}\ (3) = 27000$ USD/year

It is clear that the different between $Z_{42}^{\Sigma}\ (2)$ and $Z_{42}^{\Sigma}\ (3)$ is a year expenditure of a pipe line between buildings 2 and 3.

Building 4 has an individual heat supply system from a boiler h_{32} (see table 3).

$Z_{32}^{\Sigma}\ (4) = 33100$ USD/year

Optimal (minimal) meaning of thermoeconomical expenditures for all cottage complex is

$Z_{min} = Z_{11}^{\Sigma}(1) + Z_{42}^{\Sigma}\ (2) + Z_{42}^{\Sigma}\ (3) + Z_{32}^{\Sigma}\ (4) + \ = 97320$ USD/year

4. CONCLUSION

The problem of optimisation of heating systems has to be solved separately from the problem of optimisation of other energy intensive systems. On the basis of the unique features of such a system it is possible to build an effective procedure for optimisation. The suggested method based on development and analysis of thermoeconomical expenditure graph. It allows one to find the optimal variant for this kind of systems with different types and numbers of heat consumers.
An example of optimal synthesis of a real cottage complex heating system is given.

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