DOI: https://doi.org/10.15276/hait.05.2022.3
UDC 004.662.99·519.6

Improvement of design of heat networks: parallel-series connection

Georgy V. Derevyanko[1)]
ORCID: http://orcid.org/ 0000-0002-5895-4478; nsd@te.net.ua
Vladimir I. Mescheryakov[2)]
ORCID: http://orcid.org/ 0000–0003–0499–827X; gradan@ua.fm. Scopus Author ID: 57192640885
[1)] System Technology Solutions, 51 Holsteische Str. Berlin, 12163, Germany
[2)] State Environmental University, 15, Lvivska Str. Odessa, 65026, Ukraine

ABSTRACT

An analytical model of the system has been developed, consisting of a parallel-series connection of thermal devices. On the basis of graph theory, a system of equations of communication between the graphical representation of the system and the table of integers, which are the numbers of nodes and branches, is presented. Mathematical formalization made it possible to create a data representation that describes the distribution of temperatures in the nodes of the system and flows on its branches and reduce the volume of the problem based on expert estimates corresponding to the second law of thermodynamics. The chains and routes of heat distribution in the network of heat exchangers, including input and output elements, distribution and mixing units, are considered. The presented data structure provides an opportunity to programmatically build a system of energy balance equations for the system. The system of equations is supplemented by the hypothesis of the proportionality of the change in the measure of energy in the element to the potential applied to them. As a result, a system of equations is obtained, which forms a complete problem written in matrix form. In the design problem, after determining the requirements for the system, in the mathematical sense, the problem arises of determining the elements of the matrix by the value of the determinant. The requirement of equilibrium in the nodes of mixing flows, together with the conservation law, allows us to formulate a complete system of equations that determines the distribution of flows on the branches of networks. The principle of minimum uncertainty allows us to identify a group of roots that has maximum efficiency when the principle of equilibrium is fulfilled for the elements of the system. An example is presented that implements the exact scheme for solving the design problem for a given ratio of flows at the input to the system and the requirement for its efficiency.

Keywords: Design; heat exchangers; conservation law; nodes; graph branches; system of equations; efficiency; equation roots

***For citation*: Derevyanko G. V., Mescheryakov V. I. Improving the designing method of thermal networks: parallel series connection. *Herald of Advanced Information Technology*. 2022; Vol. 5, No.1: 32–39. DOI: https://doi.org/10.15276/hait.05.2022.3**

INTRODUCTION

The design of chemical production is associated with the analysis of processes and the synthesis of a system of constituent apparatuses in which heating and cooling of a substance and the exchange of heat flows take place. The design problem can be considered as a mathematical programming problem, despite the complexity and large dimension. A system is defined as a combination of elements of technological processes and a communication system between them. The main problems in the computer implementation of the systems approach is the development of methods for describing tasks and methods for solving them. In this formulation, in addition to problems with the solution method, there arises the fundamental problem of the existence of a solution to such a system of equations and, as a consequence, the appearance of questions about the quality of the results obtained. Along with the difficulties in the formation of a system of equations in most practical problems, the values of variables are determined on the basis of solving a system of nonlinear equations for the material and heat balance of chemical-technological systems. Systems of computer-aided design of heat networks involve the allocation of characteristic connections of the elements of the system. The relevance of further research is due to the need for a formal description of a parallel-series circuit, as one of the typical connections of a heat network.

LITERATURE REVIEW

The cost of heating and cooling a substance in the production cycle is a significant share in value terms of the total energy costs and reaches 50 % [1]. With regard to the analysis of heat supply networks, it is shown in [2] that the main thermophysical indicators significantly depend on the design parameters of heat exchangers, the network topology, and the characteristics of heat carriers. An important direction for systems for designing heat networks are on-board systems, for which stringent requirements are imposed on mass and overall refineries, a reduction in the consumption of energy resources by up to 30-50 % has been achieved [17]. The software package Aspen HYSYS has been created, designed for thermal design of chemical production, which is currently the world leader [18]. The presented modeling methods use iterative methods of data processing, and the main problems associated with the incompleteness of the original system of equations and the principle of data processing are not solved. This circumstance does not allow us to talk about optimal design, which is extremely important for processes with a significant share of the energy component. The relevance of changing the concept in the design of heat exchange systems is substantiated in [19], where the possibility of optimally solving the problem by using analytical models is shown. In the system of heat exchangers, serial, parallel, bypass and loop connections are distinguished, which can be considered elementary connections inherent in any complex heat exchange network. In [20], an analytical model of a serial connection of heat exchangers is presented, in [21] of a bypass connection, in which an objective approach is proposed to replenish the original system of equations and obtain optimal design solutions. An urgent task for further research is the development of an analytical model for the parallel-series connection of heat exchangers that meet the optimization conditions.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this work is to obtain an analytical relationship for the distribution of heat transfer efficiency in a system of parallel-series connection of heat exchangers.

To achieve this goal, the following tasks have been set:

1) to develop an analytical model of a parallel-series connection of heat exchangers.

2) to analyze the developed model to determine the main design indicators: efficiency and heat transfer surface.

ANALYTICAL MODEL OF ASSOCIATION OF DEVICES

We define design as a problem of mathematical programming, despite the complexity of the description and the large dimension of expressions. The system is considered as a combination of elements of the technological cycle and the connection between them to achieve a specific goal and is represented by a network structure. Consider a parallel-series connection as a typical connection in heat exchange networks of industrial production (Fig. 1). The cold flow propagates along the channel (7-100), while the hot flow propagates along the channel (0-60).

The main problems in the computer implementation of the systems approach are the development of both methods for describing problems and methods for solving them. In this formulation, in addition to problems with the solution method, there is a fundamental problem of the existence of a solution to such a system of equations and, as a result, questions arise about the quality of the results obtained. Along with the difficulties in the formation of a system of equations, in most practical problems, the values of variables are determined on the basis of solving a system of nonlinear equations (material and heat balance of CTS), as in modeling programs (ASPEN PLUS, PRO II, CHEMCAD).

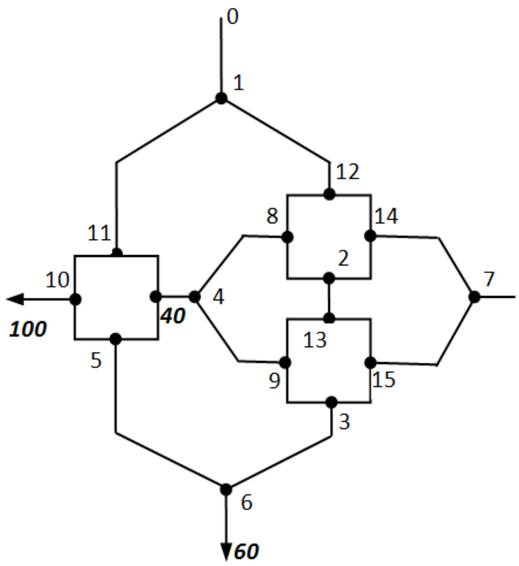

Fig. 1. **Parallel-series connection of heat exchangers**
Source: **compiled by the authors**

The application of graph theory has become generally accepted in the formalization of the description of systems. Despite the generality of the approach based on graph theory, the main differences arise in their construction and definition of operations on them. Due to the large dimension of the problem, the main question is the possibility of constructing a system of equations programmatically using one or another form of the graph. This establishes the relationship between the engineering graphical representation of the system (Fig. 1) and the table of integers, which are the numbers of nodes and branches (Fig. 2 and Fig. 3).

1	0	1	
2	1	11	
3	11	5	1.1
4	5	6	
5	6	60	
6	1	12	
7	12	2	2.1
8	2	13	
9	13	3	3.1
10	3	60	

Fig. 2. **The graph of the "hot" network presented in Fig. 1**
***Source:* compiled by the authors**

The graphical representation of the system, shown in Fig. 1, describes the topological image of the real system, and the matrices shown in Fig. 2 and Fig. 3 are a formal form of its mathematical display.

	0	1	11	5	6	60	12	2	13	3
0	0	1	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	1	0	0	0
11	0	0	0	1	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	1	0
13	0	0	0	0	0	0	0	0	0	1
3	0	0	0	0	0	1	0	0	0	0

Fig. 3. **Adjacency matrix**
***Source:* compiled by the authors**

Mathematical formalization of the description of a real problem based on graph theory makes it possible, firstly, to create a data structure for constructing systems of equations that determine the distribution of temperatures at the nodes of the system and flows on its branches. Secondly, this approach allows us to reduce the volume of the problem based on expert assessments that do not contradict the second law of thermodynamics. So, the total number of nodes in the system shown in Fig.1 is ten

$$\vec{T} = (T_0 \ \ T_1 \ \ T_{11} \ \ T_5 \ \ T_6 \ \ T_{12} \ \ T_2 \ \ T_{13} \ \ T_3 \ \ T_{60})\,. \qquad (1)$$

Let us define the concept of a chain as a finite set of node numbers satisfying the condition T_n = idem.

$$\vec{U} = (U_1 \ \ U_2 \ \ U_3 \ U_4 \ \ U_5 \ \ U_6 \ \ U_7 \ \ U_8 \ \ U_9 \ \ U_{10})\,. \qquad (2)$$

Let us define the concept of a route as a finite set of branch numbers that satisfy the conditions: U_n = idem and V_n = idem.

Similar constructions define the data structure for a "cold" network. The introduced concepts of the chain, together with the rule for choosing the node number, make it possible to construct matrices A and B. The matrix components determine the numbers of the input and output nodes of the "hot" and "cold" flows in the elements of the inter-grid and intra-grid energy exchange, respectively

$$A = \begin{pmatrix} 1 & 0 & 10 & 5 & 41 \\ 2 & 0 & 7 & 2 & 8 \\ 3 & 2 & 7 & 3 & 9 \end{pmatrix} \qquad B = \begin{pmatrix} 5 & 5 & 3 & 61 & 62 \\ 6 & 8 & 9 & 41 & 42 \end{pmatrix}. \qquad (3)$$

In turn, the described data structure makes it possible to programmatically construct a system of energy balance equations for the system shown in Fig. 1.

$$\begin{aligned} \alpha_1(T_0 - T_5) &= T_{10} - T_{41} \\ \alpha_2(T_0 - T_2) &= T_8 - \Theta_0 \\ \alpha_3(T_2 - T_3) &= T_9 - \Theta_0 \\ \alpha_4(T_5 - T_{61}) &= T_{62} - T_3 \\ \alpha_5(T_8 - T_{41}) &= T_{42} - T_9 \end{aligned} \ . \qquad (4)$$

Let us supplement the system of equations (4) with the hypothesis that the change in the measure of energy in the element is proportional to the potential applied to it

$$\begin{aligned} T_0 - T_5 &= \Phi_1(T_0 - T_{41}) \\ T_0 - T_2 &= \Phi_2(T_0 - \Theta_0) \\ T_2 - T_3 &= \Phi_3(T_2 - \Theta_0) \\ T_3 - T_{61} &= \Phi_4(T_5 - T_3) \\ T_8 - T_{41} &= \Phi_5(T_8 - T_9) \end{aligned} \ . \qquad (5)$$

Systems of equations (4) and (5) form a complete problem that can be written in matrix form as

$$\begin{pmatrix} -\alpha_1 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & -\alpha_2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & \alpha_3 & -\alpha_3 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ \alpha_4 & 0 & 1 & -\alpha_4 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & -\alpha_5 & 0 & \alpha_5 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & \Phi_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-\Phi_3 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1-\Phi_4 & 0 & \Phi_4 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1-\Phi_5 & \Phi_5 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} T_5 \\ T_2 \\ T_3 \\ T_{61} \\ T_{41} \\ T_{10} \\ T_8 \\ T_9 \\ T_{62} \\ T_{42} \end{pmatrix} = \begin{pmatrix} -\alpha_1 T_0 \\ -\alpha_2 T_0 - \Theta_0 \\ -\Theta_0 \\ 0 \\ 0 \\ (\Phi_1 - 1)T_0 \\ \Phi_2 (T_0 - \Theta_0) - T \\ -\Phi_3 \Theta_0 \\ 0 \\ 0 \end{pmatrix} \quad (6)$$

In the problem of modeling with known values α_n and Φ_n the solution of such a system of equations does not cause significant problems. In the design problem, when only the requirements for the system are defined, in the mathematical sense, the problem arises of determining the elements of the matrix by the value of the determinant.

The requirement of equilibrium at the mixing nodes, together with the law of conservation of flows, allows us to formulate a complete system of equations that determines the distribution of flows on the branches of networks

$$\Theta_{41} - \Theta_{42} = (\alpha_5 \Phi_5 + \Phi_5 - 1) \cdot \cdot (\alpha_2 \Phi_2 - \alpha_3 \Phi_3 + \alpha_3 \Phi_2 \Phi_3)$$

$$\Theta_{41} - \Theta_{42} = -(\alpha_4 \Phi_4 + \Phi_4 - 1) \cdot \cdot (\Phi_2 \Phi_3 + \Phi_1 - \Phi_2 - \Phi_3 - - \alpha_2 \Phi_1 \Phi_2 + \alpha_2 \Phi_1 \Phi_2 \Phi_5 - - \alpha_3 \Phi_1 \Phi_3 \Phi_5 + \alpha_3 \Phi_1 \Phi_2 \Phi_3 \Phi_5)$$

$$U_0 - (U_1 + U_2) = 0 \qquad V_0 - (V_1 + V_2) = 0$$

$$\alpha_4 U_2 - U_1) = 0 \qquad \alpha_5 V_2 - V_1 = 0$$

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ -1 & \alpha_4 & 0 & 0 \\ 0 & 0 & -1 & \alpha_5 \end{pmatrix} \cdot \begin{pmatrix} U_1 \\ U_2 \\ V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} U_0 \\ V_0 \\ 0 \\ 0 \end{pmatrix} . \quad (7)$$

In turn, this allows us to construct a solution to the problem of flows and their relations in elements as a function of the efficiencies of intranet energy exchange [21]

$$\begin{pmatrix} U_1 \\ U_2 \\ V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} \dfrac{U_0\,\alpha_4}{\alpha_4 + 1} \\ \dfrac{U_0}{\alpha_4 + 1} \\ \dfrac{V_0\,\alpha_5}{\alpha_5 + 1} \\ \dfrac{V_0}{\alpha_5 + 1} \end{pmatrix} = \begin{pmatrix} U_0 (1 - \Phi_4) \\ U_0 \Phi_4 \\ V_0 (1 - \Phi_5) \\ V_0 \Phi_5 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \end{pmatrix} = \begin{pmatrix} \alpha_0 (1 - \Phi_4) \\ \alpha_0 \dfrac{\Phi_4}{1 - \Phi_5} \\ \alpha_0 \dfrac{\Phi_4}{\Phi_5} \\ \dfrac{1 - \Phi_4}{\Phi_4} \\ \dfrac{1 - \Phi_5}{\Phi_5} \end{pmatrix} . \quad (8)$$

ANALYSIS OF THE MAIN FEATURES OF THE ANALYTICAL MODEL

In [19, 20], [21], principles are formulated that allow one to obtain a system of equations for determining the efficiencies of intra-grid and inter-grid energy exchange.

Denote

$$x = \Phi_1 \quad y = \Phi_2 \quad z = \Phi_3 \quad \xi = \Phi_4 \quad \zeta = \Phi_5 .$$

The requirement for a minimum uncertainty for the average parameters of the system leads to the equations

$$\sum_{n=0}^{12} \left(A_n \cdot z^n \right) = 0 \quad y = z . \quad (9)$$

$$\begin{pmatrix} A_0 \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \\ A_{11} \\ A_{12} \end{pmatrix} = \begin{pmatrix} -E(32E^2\alpha^2 - 32E\alpha + 9 \\ -2(32E^3\alpha^3 - 24E^3\alpha^2 - 112E^2\alpha^2 + 24E^2\alpha + 71E\alpha - 9E - 9 \\ 128E^3\alpha^3 - 16E^3\alpha^2 + 192E^2\alpha^3 - 448E^2\alpha^2 + 16E^2\alpha - 440E\alpha^2 + 311E\alpha - 15E + 140\alpha - 45 \\ -2(40E^3\alpha^3 + 240E^2\alpha^3 - 140E^2\alpha^2 + 24E\alpha^3 - 520E\alpha^2 + 109\alpha - 3E - 120\alpha^2 + 190\alpha - 24) \\ 16E^3\alpha^3 + 432E^2\alpha^3 - 56E^2\alpha^2 - 80E\alpha^4 + 264\alpha^3 - 910E\alpha^2 + 61E\alpha - E - 160\alpha^3 - 600\alpha^2 + 355\alpha - 27 \\ -2(84E^2\alpha^3 - 16E\alpha^5 - 80E\alpha^4 + 194E\alpha^3 - 175E\alpha^2 + 4E\alpha - 80\alpha^4 - 160\alpha^3 - 310\alpha^2 + 70\alpha - 4) \\ 24E^2\alpha^3 - 80E\alpha^5 - 120E\alpha^4 + 246E\alpha^3 - 50E\alpha^2 + E\alpha - 64\alpha^5 - 400\alpha^4 - 240\alpha^3 - 330\alpha^2 + 20\alpha - 1 \\ 2\alpha^2(40\alpha + 20E\alpha^2 + 40E\alpha^3 + 200\alpha^2 + 96\alpha^3 - 36E\alpha + 45) \\ -\alpha^2(10\alpha + 5E\alpha^2 + 40E\alpha^3 + 200\alpha^2 + 240\alpha^3 - 8E\alpha + 10) \\ 10\alpha^4(16\alpha + E\alpha + 5) \\ -\alpha^4(50\alpha + E\alpha + 5) \\ 12\alpha^5 \\ -\alpha^5 \end{pmatrix}. \quad (10)$$

$$x = \frac{\xi x^2 - 2\xi z + E}{(\xi - 1)\cdot(\xi\alpha_0 z^2 - 2\xi\alpha_0 z + 1)}. \quad (11)$$

It is obvious that equations (8-11) form 12 groups of roots; however, the principle of minimum uncertainty allows us to select a group of roots that has maximum efficiency when the principle of equilibrium is fulfilled for the elements of the system.

DISCUSSION OF THE RESULTS OF THE ANALYSIS

Consider an example that implements the exact scheme for solving the design problem for the system shown in Fig. 1 for a given ratio of flows at the system inlet α = 0.7 and the requirement for its efficiency E = 0.6

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \Phi_4 \\ \Phi_5 \end{pmatrix} = \begin{pmatrix} 0.6874 \\ 0{,}4301 \\ 0{,}4301 \\ 0{,}4302 \\ 0.5188 \end{pmatrix}. \quad (12)$$

The obtained values of efficiencies allow us to determine the amount of energy on the elements of the system

$$\begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \end{pmatrix} = (T_0 - \Theta_0)\cdot\begin{pmatrix} U_1\Phi_1 & 0 & 0 \\ 0 & U_2\Phi_2 & 0 \\ 0 & 0 & U_2\Phi_3 \end{pmatrix}\cdot\begin{pmatrix} \Pi_1 \\ \Pi_2 \\ \Pi_3 \end{pmatrix}. \quad 13)$$

And the distribution of flows on its branches

$$\begin{pmatrix} V_1 \\ V_2 \\ U_1 \\ U_2 \end{pmatrix} = \begin{pmatrix} V_0\ (1-\xi) \\ V_0\ \xi \\ U_0(1-\xi) \\ U_0\ \xi \end{pmatrix} = \begin{pmatrix} 0{,}5697 \\ 0.4302 \\ 0.4811 \\ 0.5188 \end{pmatrix}. \quad (14)$$

Here Π in relations (13) determines the energy potential at the input to the elements of the system

$$\begin{pmatrix} \Pi_1 \\ \Pi_2 \\ \Pi_3 \\ \Pi_4 \\ \Pi_5 \end{pmatrix} = \left(\begin{pmatrix} 0.7547 \\ 1 \\ 0.5698 \\ 0.1563 \\ 0.0672 \end{pmatrix}\right). \quad (15)$$

The given results, taking into account the system of equations (6), allow us to obtain the temperature values at the network nodes

$$\begin{pmatrix} \Theta_5 \\ \Theta_2 \\ \Theta_3 \\ \Theta_{61} \\ \Theta_{41} \end{pmatrix} = \begin{pmatrix} 0{,}5229 \\ 0{,}4301 \\ 0.6752 \\ 0.5884 \\ 0.7607 \end{pmatrix} \begin{pmatrix} \Theta_{10} \\ \Theta_8 \\ \Theta_9 \\ \Theta_{62} \\ \Theta_{42} \end{pmatrix} = \begin{pmatrix} 0{,}5845 \\ 0.7258 \\ 0.7930 \\ 0.6144 \\ 0.7468 \end{pmatrix}. \quad (16)$$

Having a complete picture of the behavior of the system, we choose counter flow type heat exchangers as its elements, the efficiency of which is determined by the ratio of the form

$$\Phi = \frac{1 - \exp[-NTU(1-\alpha)]}{1 - \alpha\exp[-NTU(1-\alpha)]}. \quad (17)$$

The solution of the transcendental equation (17) makes it possible to obtain the values of NTU

$$NTU_1 = 0.6527$$
$$NTU_2 = 0.3461.$$
$$NTU_3 = 0.3702$$

To assess the quality of the solution, we use the results of [20], which show the equivalence of the efficiency of one device to a system of N devices with a parallel connection

$$NTU_0 = 1{,}2385 .$$

Thus, a system with a parallel-series connection has about 10 % more metal consumption compared to a system with a parallel connection of elements.

CONCLUSIONS

1. An analytical model of a parallel-series connection of heat exchangers has been developed, which is inherent in the principles of the existence of a solution (completeness of the original system of equations) and ensuring the quality of the solution (optimization).

2. Description of the heat exchange network by a graph allows you to determine the topographic image of a real system and obtain a complete system of primary equations. The representation of this system in a matrix form provides the possibility of solving the problem of flows and their relations in elements as a function of the efficiencies of intra-network energy exchange.

3. An analysis of the developed model was carried out to determine the main design indicators: efficiency and heat transfer surface. It is shown that the principle of minimum uncertainty makes it possible to single out a group of roots that has maximum efficiency when the principle of equilibrium is fulfilled for the elements of the system.

4. An example of the implementation of an exact scheme for solving the design problem for counterflow heat exchangers is presented, the values of efficiencies, the distribution of flows in the branches, and the energy potentials at the entrance to the system elements are obtained. The gain in reducing the required metal consumption in comparison with the standard design method is shown, which is especially important for on-board systems.

REFERENCES

1. Woolley, E., Luo, Y. & Simeone, A. “Industrial waste heat recovery: A systematic approach”. *Sustainable Energy Technologies and Assessments*. 2018; Vol. 29: 50–59. DOI: https://doi.org/10.1016/j.seta.2018.07.001.

2. Nussbaumer, T. & Thalmann, S. “Influence of system design on heat distribution costs in district heating”. *Publ. Energy*. 2016; Vol. 101, 15: 496–505. DOI: https://doi.org/10.1016/j.energy.2016.02.062.

3. Amano, Y., Hashizume, T. & Fujiwara, K. “Modeling the dynamics of a two heat exchanger network connected in parallel and the effects of auxiliaries”. *Heat Transfer*. 1997; Vol.26 Issue 5: 275–290. DOI: https://doi.org/10.1002/(sici)1520-6556(1997)26:53.0.co;2-t.

4. Kainz, M., Semtsiv, M., Tsianos, G., et al. “Thermoelectric-cooled terahertz quantum cascade lasers”. *Optics Express*. 2019; Vol. 27 Issue 15: 20688–20693. DOI: https://doi.org/10.1364/OE.27.020688.

5. Qian, B., Ren, F., Zhao, Y., Wu, F. & Wang, T. “Enhanced thermoelectric cooling through introduction of material anisotropy in transverse thermoelectric composites”. *Publ. Materials*. 2019; 12: 2049 p. DOI: https://doi.org/10.3390/ma12132049.

6. Nielsen, J. B. & Pedersen, E. “On the modeling of heat exchangers and heat exchanger network dynamics using bond graphs”. *Mathematical and Computer Modelling of Dynamical Systems*. 2018; Vol. 24 Issue 6: 626–642. DOI: https://doi.org/10.1080/13873954.2018.1533566.

7. Gu, X., Wang, G., Zhang, Q. et al. “Fluid-structure interaction analysis of heat exchanger with tensional flow in the shell side”. *J Mech Sci Technol* . 2022; 36: 479–489. DOI: https://doi.org/10.1007/s12206-021-1245-1.

8. Li, W., Paul, M. C., Siviter, J., Montecucco, A., Knox, A. R., Sweet, T., Min, G., Baig, H., Mallick, T. K., Han, G., Gregory D. H. & Azough, R. F. “Thermal performance of two heat exchangers for thermoelectric generators”. *Case Studies in Thermal Engineering*. 2016; Vol. 8: 164–175. DOI: https://doi.org/10.1016/j.csite.2016.06.008.

9. Derevyanko, G. & Mescheryakov, V. “Increase of energy efficiency of direct-flow heat exchangers”. *Herald of Advanced Information Technology. Publ. Science i Technical*. Odessa: Ukraine. 2019; Vol. 2; No 4: 310–316. DOI: https://doi.org/ 10.15276/hait.04.2019.7.

10. Zaversky, F., Rodriguez-Garcia, M. M., Garcia Barberena, J., Sanchez, M. & Astrain, D. “Transient behavior of an active indirect two-tank thermal energy storage system during changes in operating mode”. An application of an experimentally validated numerical model. *Energy Procedia*. 2013; 49: 1078–1087. DOI: https://doi.org/10.1016/j. egypro.2014.03.117.

11. Omidrvardia, F., Hansen, H. N. & Sarhadi, A. “A systematic approach applied in design of a micro heat exchanger”. *The International Journal of Advanced Manufacturing Technology*. 2016; Vol.82: 1187–1195. DOI: https://doi.org/10.1007/s00170-015-7401-y.

12. Borovkova, E. A. “Modeling of technological processes with gas-phase heterogeneous catalytic reactions in the production of synthesis gas and aromatic hydrocarbons”. *Dissertation for the Degree of candidate of technical sciences.* Moscow: Russian Federation. 2016. 147 p.

13. Lapteva, T. V. “Fundamentals of methodology for solving problems of designing optimal chemical-technological systems, taking into account the uncertainty in the initial information”. *Diss. for a Job. uch. Art. Doctor of Technical Sciences Kazan.* 2014. 401 p.

14. Korobeinikov, A. & McCarthy John, E. “Mathematical modeling of internal heat recovery in flash tank heat exchanger cascades”. University in St Louis. *Mathematics-in-Industry Case Studies Journal*. Washington: 2013; Vol. 5: 43–58. DOI: https://openscholarship.wustl.edu/cgi/viewcontent.cgi?article=1019&context=math_facpubs.

15. Melian, E.; Klein, H.; Thißen, N. “Improvement of a nusselt-based simulation model for heat transfer in rotary heat exchangers”. *Energies*.2021; 14(1): 10 p. DOI: https://doi.org/10.3390/en14010010.

16. Taler, D., Trojan, M. & Taler, J. “Mathematical modeling of tube heat exchangers with complex flow arrangement”. *Chemical and Process Engineering*. 2011; 32 (1): 7–19. DOI: https://doi.org/10.2478/v10176-011-0001-y.

17. Zhulaev, S. V.*’*The pinch-analysis and optimization of industrial facilities”. *Electronic Scientific Journal “Oil and Gas Business.* 2012; No.2: 392–400. – Available at: https://www.semanticscholar.org/paper/THE-PINCH-ANALYSIS-AND-OPTIMIZATION-OF-INDUSTRIAL-Zhulaev/3fb31effb1d5252c614738476e998ced185673fb.

18. “Aspen HYSYS”. – Available at: https://www.aspentech.com/products/engineering/aspen-hysys. – [Accessed: Dec. 2020].

19. Derevyanko, G. V. & Mescheryakov, V. I. “Analytical review of design systems for heat and mass transfer networks”. *Scientific notes of TNU named after V. Vernadsky. Series: Technical Sciences.* 2019; Vol. 30 (69) No.5 Part 1: 81–91. DOI: https://doi.org/10.32838/2663-5941/2019.5-1/13.

20. Derevyanko, G. & Mescheryakov, V. “Improving the designing method of thermal networks: serial connection of streams. *Applied Aspects of Information Technology. Publ. Nauka i Tekhnika.* Odessa: Ukraine. 2021; Vol. 4 No. 2: 146–154. DOI: http://doi.org/10.15276/hait.02.2021.4.

21. Derevyanko, G. & Mescheryakov, V. “Improving the designing method of thermal networks: bypass connection. *Applied Aspects of Information Technology. Publ. Nauka i Tekhnika.* Odessa: Ukraine. 2021; Vol. 4 No. 4: 329–337. DOI: https://doi.org/10.15276/aait.04.2021.3.

Conflicts of Interest: the authors declare no conflict of interest.

Received 08.12.2020
Received after revision 25.02.2021
Accepted 15.03.2021

DOI: https://doi.org/10.15276/hait.05.2022.3
УДК 004.662.99·519.6

Вдосконалення методу проектування теплових мереж: паралельно-послідовне з’єднання

Георгій Васильович Дерев’янко[1)]
ORCID: https://orcid.org/0000-0002-5895-4478; nsd@te.net.ua
Володимир Іванович Мещеряков[2)]
ORCID: https://orcid.org/0000–0003–0499–827X; gradan@ua.fm. Scopus Author ID: 57192640885
[1)] System Technology Solutions, 51, Holsteische Str. Берлін,12163, Німеччина
[2)] Одеський державний екологічний університет, вул. Львівська, 15, Одеса, 65026, Україна

АНОТАЦІЯ

Розроблена аналітична модель системи, яка складається з паралельно-послідовного з’єднання теплових апаратів. На основі теорії графів представлено систему рівнянь зв’язку між графічним представленням системи і таблицею цілих чисел, які є номерами вузлів і гілок. Математична формалізація дозволила створити представлення даних, які описують розподіл температур у вузлах і зменшити об’єм задачі на основі експертних оцінок, що відповідають другому закону термодинаміки. Розглянуті ланцюги і маршрути розподілу тепла у мережі апаратів теплообміну, які включають вхідні і вихідні елементи, вузли розподілу і змішення. Представлена структура даних представляє можливість програмним шляхом побудувати систему рівнянь енергетичного балансу для системи. Систему рівнянь доповнено гіпотезою про пропорційність зміни міри енергії в елементі за рахунок наведеного потенціалу. В результаті одержана система рівнянь, яка створює повну задачу, записану в матричній формі. В задачі проектування, після визначення вимог до системи, в математичному сенсі виникає задача визначення елементів матриці по значенням детермінанту. Вимоги рівноваги у вузлах змішення потоків сумісно з законом збереження дозволяє сформулювати повну систему рівнянь, яка визначає розподіл потоків у гілках мережі. Принцип мінімальної невизначеності дозволяє виділити групу коренів, які володіють максимальною ефективністю при виконанні принципу рівноваги для елементів системи. Наведено приклад, що реалізує точну систему рішення при заданому відношенні потоків на вході і вимогам до її ефективності.

Ключові слова: проектування; апарати теплообміну; закон збереження; вузли; гілки графу; система рівнянь; ефективність; корні рівнянь

ABOUT THE AUTHORS

Georgy Derevyanko - Candidate of Technical Sciences, Head of Science Department System Technology Solutions 51 Holsteische Str. Berlin,12163, Germany

ORCID: https://orcid.org/0000-0002-5895-4478; nsd@te.net.ua

***Research field*:** Heat transfer in heterogeneous flows; applied mathematics; systems theory; mathematical programming

Георгій Васильович Дерев’янко – кандидат технічних наук, науковий керівник підрозділу System Technology Solutions, 51 Holsteische str., Berlin, 12163, Germany

Vladimir Mescheryakov - Doctor of Technical Sciences, Professor, Head of Department, Department of Informatics, State Environmental University, 15 Lvivska Str. Odessa, 65026, Ukraine.

ORCID: /http://orcid.org/0000-0003-0499-827X; gradan@ua.fm. Scopus Author ID: 57192640885

***Research field*:** Reliability and dynamic descriptions of thermo-electric cooling devices; design of power processes, biotechnical informative systems

Володимир Іванович Мещеряков – доктор технічних наук, зав. кафедри Інформатики Одеського державного екологічного університету, вул. Львівська, 15. Одеса, 65026, Україна