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Features of Mathematical Simulation of the Processes of Combined Heat Transfer in Waveguides

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***Abstract* — Mechanical means which are directly related to the information support path (locators, observation stations, accompaniment, detection, localization, etc.) require special attention within the framework of the technical channels of receiving information. Their accurate and stable performance is of the utmost importance. Loss of the mechanical properties occurs during operation, that is material wear. A special role in the development and study of technological systems, characterized by high temperature process conditions (in metallurgy, power engineering, mechanical engineering, etc.) is featured to the develop-ment of rational mathematical models of heat transfer processes. In practice there is a joint (compound) or a complex heat transfer, which combines heat conduction, convection and radiation heat transfer processes. Mathematical modeling method of compound (radiation-convective) heat transfer processes in techno-logical systems, based on the numerical solution of multidimensional differential heat conduction equation with complicated boundary conditions has been introduced. And at the same time finite-difference approximation of heat conduction equation and boundary conditions is obtained by integro-interpolation method (balance meth-od). A locally one-dimensional method of calculation based on heat exchange process splitting in the spatial variables is applied to solve the multidimensional problems of heat exchange. Heat transfer calculations of complex heat exchange are recommended to carry out on the base of the additive principle considering the common difficulty of numerical implementation of heat transfer problems, but when recording finite-difference approximation of boundary conditions it is advantageous to use the radiation heat exchange coefficient. The approaches considered to mathematical modeling of compound heat transfer processes can be used to investigate the thermal conditions of the process equipment in metallurgy, power engineering, mechanical engineering and other industries, as well as in the students training of university specialties. Thus, the solution of the fundamental problem of radiative heat transfer in the formulation adopted here (i.e., when a discrete consideration of temperature fields and optical constants is practically possible), ultimately comes down to calculating the angular coefficients (geometric radiation invariants) considered system of surfaces**

Keywords— model, heredity, temperature, deformation, composite materials, heredity nucleus, parameters.

I. INTRODUCTION

The labor intensity, material intensity and high cost of laboratory, semi-industrial and industrial experiments, their limitations, multidimensionality and nonlinearity of the main processes and developments, as well as the progressive development of computer technology and software scale, have significantly updated theoretical research (mathematical modeling).

Mechanical means which are directly related to the information support path (locators, observation stations, accompaniment, detection, localization, etc.) require special attention within the framework of the technical channels of receiving information. Their accurate and stable performance is of the utmost importance. Loss of the mechanical properties occurs during operation, that is material wear.

A special role in the development and study of the path of information support, characterized by high-temperature conditions of the processes (in metallurgy, energy, mechanical engineering, etc.), is assigned to the creation of rational mathematical models of heat transfer processes.

II. RECENT RESEARCH ANALYSIS

As is known [1], the basis of mathematical models of the mentioned processes is the differential equation of heat conduction, which connects temporal and spatial temperature changes of the designed or investigated process, unit, structure, etc:

$$c\rho\frac{\partial T}{\partial \tau} = div(\lambda\, grad\, T) + q_V, \qquad (1)$$

where c - heat capacity; ρ - density; T - temperature; τ - time; λ - thermal conductivity; q_V- power of internal heat sources.

Equation (1) can be used to solve specific problems of heat conduction if it is supplemented by appropriate boundary conditions (singularity conditions), among which

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are boundary conditions characterizing the process of heat exchange between the body surface and the environment.

In practice, usually there is a joint (combined) or complex heat transfer that combines the processes of heat conduction, convection and radiation (radiant) heat transfer. Among the processes of complex heat transfer, radiation-convectional heat transfer is the most general case, in which the heat is transferred not only by radiation, but also by conduction and convection [1-3].

Therefore, in most practical problems, boundary conditions of type III with known patterns of heat exchange between the body surface and the medium prevail.

In view of the extreme complexity of the obtained solutions, the estimated calculations of complex heat exchange can be carried out on the basis of the additivity principle - separately and independently calculate the radiative and convective components of heat flows, and sum up the results [1].

III. Goals And Objectives Of The Article

Lets consider features of numerical solution of the following problem of combined (radiation and convection) heat transfer in the absence of internal heat sources:

$$c\rho\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right); \quad (2)$$

$$-\lambda\left(\frac{\partial T}{\partial x}\right)_S = \alpha_k(T_S - T_0) + \sigma_0 a_S \sum_{j=1}^{n} a_j \Phi_{Sj}\left(T_S^4 - T_{r_j}^4\right); \quad (3)$$

$$T(x,0) = T_0, \quad (4)$$

where x is the corresponding coordinate; α is the heat transfer coefficient; σ_0 is the Stefan-Boltzmann constant; a is the surface absorptivity; Φ is the resolving angular radiative coefficient; T_0 is the initial temperature of the incoming flow away from the surface (or ambient temperature); Tr is the temperature of the surfaces involved in the radiative heat transfer [2-5].

The index S (from surface) in (3) denotes the surface of the calculation region, and the indices k and r are the convective and radiative components of the complex heat exchange, respectively [6].

In this formulation of the problem, there are identical complex heat transfer conditions on both boundary surfaces (3).

IV. Main Part

In the boundary conditions (3) along with the traditional Newton-Richman law describing the convective component of the combined heat transfer, there is an expression [4] to account for the flux density of the resulting radiation in a closed system of n radiating gray bodies separated by a transparent (diathermal) medium. In this case the problem of radiation heat transfer is eventually reduced to finding geometrical invariants of radiation, namely its angular coefficients [7-9].

The study of heat transfer by radiation in closed systems formed by an opaque surface of arbitrary configuration is of interest for many engineering applications. If the temperature distribution is given on the entire boundary surface, and it is required to find the resulting radiation fluxes (q_r), the problem statement is usually called fundamental.

In engineering practice of solving the integral equations of radiative heat transfer for a system of bodies separated by a transparent (diathermic) medium, due to the complexity of the initial problem, a number of simplifications have to be introduced. The most commonly accepted assumption is the diffuseness of radiation and reflection and gray or monochromatic radiation, which is characterized by a constant density in isothermal areas of the system surface. In this approximation, calculations require minimal initial information - radiation and optical-geometric characteristics of the system of bodies under consideration.

The solution of the integral equations of radiative heat transfer can be carried out by analytical and numerical methods. Exact analytical solutions are possible only for simple geometric configurations of radiating systems. Therefore, in view of the great computational difficulties in implementing the problems of radiant heat transfer, in engineering calculations, approximate analytical and numerical methods are resorted to. Numerical methods for reducing linear integral equations to a finite system of linear algebraic equations or the so-called zonal methods find the greatest distribution for solving practical problems of radiative heat transfer.

The essence of zonal methods is [10, 15] that the surface F of the radiating system is divided into an arbitrary number of zones n, under the condition $F = \sum_{i=1}^{n} F_i$. Within each zone, the temperature and radiation characteristics of the surface are constant. Consequently, the continuous temperature distribution and the optical characteristics of the radiating system are replaced by discontinuous (discrete), in which the field of the indicated characteristics is considered to consist of a finite number of thermally and optically homogeneous sections (bodies, zones). In this case, the original integral equation of radiative heat transfer is replaced by a system of integral equations (one for each zone). By the way, this approach is very convenient for the grid solution of the heat equation.

If a continuous temperature distribution is specified on the surface, the degree of accuracy of approximation of the original integral equation by the system of equations depends on the number of zones into which the surface is divided. As $n\to\infty$, the system of integral equations degenerates into one exact integral equation.

If we add here another assumption accepted in zonal methods, namely, the equality of the local slope to the average, the system of integral equations turns into a system of algebraic equations of radiative heat transfer, which underlies the zonal methods. The greater the number of allocated zones, the more reliable the solution obtained.

Thus, the solution of the fundamental problem of radiative heat transfer in the formulation adopted here (i.e., when discrete consideration of the temperature fields and optical constants is practically possible), ultimately reduces

to calculating the slope coefficients (geometric radiation invariants) of the considered system of surfaces.

Calculation of angular radiation coefficients for complex geometric systems may represent a rather complicated mathematical problem. The values of angular coefficients are determined by the shape, sizes of radiating surfaces, as well as the mutual location in space of the bodies that are in a state of radiative heat exchange. Besides, it is not always possible to reduce the system under consideration to the system of classical geometry, which introduces additional difficulties into the calculation technique. All this ultimately complicates the algorithm for solving the problem of radiation heat exchange [10-12].

For $n < 3$ the radiation heat transfer problems are considerably simplified, being reduced to common classical problems [13].

Differential schemes for differential equation (1) should correctly reflect in the grid function space the main properties of the original problem, such as self-coupling, familiar definiteness, etc. For complex problems described by nonlinear equations or equations with variable coefficients, a simple replacement of derivatives by finite differences cannot be considered acceptable because it will lead to schemes with a large error unsuitable for calculation. In this connection, an important task is to obtain so-called conservative difference schemes whose numerical solutions satisfy the energy conservation law [14-18].

Based on the above, difference schemes for the nonlinear differential heat conduction equation (1) are usually obtained [5, 15-18] not by the traditional method (from approximation of the differential equation operators), but by the integro-interpolation or balance method (from direct approximation of heat balance relations written for elementary volumes). In this process, expressions are used for heat fluxes at the boundaries to ensure that the conditions of agreement are fulfilled [19-23]. In this case, for heat fluxes at the boundaries, expressions are used that ensure the fulfillment of the matching conditions.

The main stages of applying the heat balance method are as follows:

- the area in which the solution is sought is divided into elementary volumes (cells) built around each grid node;

- for all internal and boundary cells, heat balance equations are written, including the values of heat fluxes at the cell boundaries; when writing balance equations for cells adjacent to boundaries, boundary conditions are used;

- the terms included in the heat balance equations are approximated, i.e. these terms are expressed in terms of grid function values; in this case, the approximation expressions for heat fluxes must satisfy the matching condition.

Since the number of cells is equal to the number of nodes of the spatial partition, then as a result of the above actions, a complete system of algebraic equations is obtained - a difference scheme, by solving which it is possible to determine the difference solution.

In addition, in the numerical simulation of continuous processes of combined heat exchange, the use of unconditionally stable implicit calculation schemes instead of conditionally stable and inefficient explicit schemes is more often resorted to [22].

Therefore, for equation (2) and boundary conditions (3) let us write an implicit difference scheme constructed by the integro-interpolation method:

- for the boundary points:

$$c_1\rho_1\frac{T_1^\tau - T_1^{\tau-\Delta\tau}}{\Delta\tau} = \frac{2}{\Delta x}\left[\alpha_k(T_0 - T_1^\tau) + \right.$$
$$\left. + \sigma_0 a_1 \sum_{j=1}^{n} a_j \Phi_{1j}\left(T_{r_j}^4 - (T_1^\tau)^4\right) - \frac{\lambda_{1+1/2}}{\Delta x}(T_1^\tau - T_2^\tau)\right]; \quad (5)$$

$$c_N\rho_N\frac{T_N^\tau - T_N^{\tau-\Delta\tau}}{\Delta\tau} = \frac{2}{\Delta x}\left[\frac{\lambda_{N-1/2}}{\Delta x}(T_{N-1}^\tau - T_N^\tau) - \right.$$
$$\left. - \alpha_k(T_N^\tau - T_0) - \sigma_0 a_N \sum_{j=1}^{n} a_j \Phi_{Nj}\left((T_N^\tau)^4 - T_{r_j}^4\right)\right]; \quad (6)$$

– for internal points ($i = \overline{2, N-1}$):

$$c_i\rho_i\frac{T_i^\tau - T_i^{\tau-\Delta\tau}}{\Delta\tau} = \frac{1}{\Delta x^2}\left[\lambda_{i-1/2}(T_{i-1}^\tau - T_i^\tau) - \right.$$
$$\left. - \lambda_{i+1/2}(T_i^\tau - T_{i+1}^\tau)\right], \quad (7)$$

where the effective thermal conductivities of the segments can be calculated, for example, by the formula [5]:

$$\lambda_{i\pm1/2} = \frac{2\lambda(T_i)\lambda(T_{i\pm1})}{\lambda(T_i)+\lambda(T_{i\pm1})}.$$

The considered one-dimensional problem (2)-(4) can be simply extended to the multidimensional cases using the so-called local-indimensional scheme of splitting by spatial variables, which combines the advantages of explicit (small machine time consumption at a time step) and implicit schemes (unconditional stability) [18].

In local-one-dimensional schemes, the course of a multidimensional physical process at each time step is represented as a result of successive realization of corresponding one-dimensional processes, each of which starts from a field distribution that arose after the end of the previous one-dimensional process. On the basis of such splitting of the problem into spatial variables, modeling of one-dimensional processes is carried out using implicit schemes and sequential action of processes is considered essentially explicitly, i.e. solution of a multidimensional problem is reduced to calculation at each time step of a set of one-dimensional problems. Application of implicit approximation of one-dimensional problems provides unconditional stability of the scheme [12].

The method of compiling a system of finite-difference equations of a locally one-dimensional scheme can be given the following physical interpretation. At the first stage, the region is replaced by a set of horizontal rods that are thermally insulated from each other, for each of which the corresponding implicit finite-difference scheme is written

using the balance method, which takes into account the boundary conditions of the problem on the vertical boundaries as the boundary conditions for the ends of the rod.

In this case, for the lower and upper horizontal rods, their lateral heat exchange with the medium is not taken into account. Therefore, the system of equations for the first and last horizontal rows of elementary volumes is completely identical to the system of equations for the inner row, which simplifies the calculation. At the next stage, in a similar way, finite-difference equations are compiled for vertical rods, and so on (in the case of a spatial problem).

The local one-dimensional scheme is naturally transferred to the cylindrical coordinate system with splitting in radial, angular and axial coordinates (or in two of the indicated directions in the case of a two-dimensional problem).

The local one-dimensional scheme can also be used for stepped regions, the boundaries of which are formed in the two-dimensional case by straight lines parallel to the coordinate axes, and in the three-dimensional case by planes parallel to the coordinate planes.

When considering the approximation property, a special concept of the so-called total approximation is introduced, which consists in the following. Each of the intermediate systems of difference equations separately does not have the property of approximation. However, the discrepancy that occurs at the first step of splitting is compensated for at subsequent stages, so that, in general, an approximation error is obtained that tends to zero when the space-time grid is refined.

When developing a locally one-dimensional scheme for splitting a multidimensional heat equation, the time step value must be chosen in such a way that the difference between the final and intermediate temperature fields does not exceed the temperature changes per time step, or at least has the same order of magnitude.

The method of total approximation makes it possible to split complex problems into a sequence of simpler ones and significantly simplify the solution of a wide class of multidimensional problems of mathematical physics. Using splitting in spatial variables, almost any numerical algorithm can be naturally generalized to the multidimensional case. The original problem is thus reduced to finding "good" one-dimensional schemes.

So, when solving multidimensional problems of combined heat exchange the sequential solution of one-dimensional problems of type (2) - (4) is carried out taking into account the number of splitting of heat exchange process by directions of heat flow distribution, i.e. adopted coordinate system [11].

The system of heat balance equations for any of splitting directions by spatial variables can be written in the following canonical form:

$$A_i T_{i-1} - C_i T_i + B_i T_{i+1} + F_i = 0, (i = \overline{1,N}), \qquad (8)$$

where $A_1 = B_N = 0$.

The boundary value problem (4) is a system of linear algebraic equations with a tridiagonal matrix, which allows us to organize calculations by the modified Gauss method, i.e., by the method of runs [40].

Classical algorithm of numerical realization of this method requires initial calculation of coefficient values Ai, Bi, Ci, Fi of equations system (8) for their subsequent substitution in appropriate equations.

So to solve the problem (2)-(4) by method of runs it is enough to reduce the system of heat balance equations (5)-(7) to canonical form (8).

However, when directly writing the expression for calculating the flux density of radiation heat exchange into the finite-difference equations (5) and (6), the problem of their further reduction to the form (4) appears, where all temperatures near the coefficients *Ai*, *Bi*, *Ci* should be written in the first degree [11-13].

In avoiding this problem, when writing the finite-difference approximation of boundary conditions for the heat conduction equation describing the combined (radiation-convective) heat transfer, it is advisable to use the radiation heat transfer coefficient [12]:

$$\alpha_r = \frac{q_r}{\Delta T_p}, \qquad (9)$$

where *qr* is the heat flux density due to radiation heat transfer; ΔTp is the design temperature head

$(\Delta T|T_S - T_r|_p)$,

So the boundary conditions (5) and (6) with regard to (5) take the following form, respectively:

$$c_1\rho_1\frac{T_1^\tau - T_1^{\tau-\Delta\tau}}{\Delta\tau} = \frac{2}{\Delta x}\left[\alpha_k(T_0 - T_1^\tau) + \sum_{j=1}^{n}\alpha_{r_j}\left(T_{r_j} - T_1^\tau\right) - \right.$$

$$\left. - \frac{\lambda_{1+1/2}}{\Delta x}(T_1^\tau - T_2^\tau)\right]; \qquad (10)$$

$$c_N\rho_N\frac{T_N^\tau - T_N^{\tau-\Delta\tau}}{\Delta\tau} = \frac{2}{\Delta x}\left[\frac{\lambda_{N-1/2}}{\Delta x}(T_{N-1}^\tau - T_N^\tau) - \right.$$

$$\left. - \alpha_k(T_N^\tau - T_0) - \sum_{j=1}^{n}\alpha_{r_j}\left(T_N^\tau - T_{r_j}\right)\right]. \qquad (11)$$

Now from equations (10), (11) and (5) it is easy to derive calculation formulas for equation (4) coefficients and then find solution of problem (3) - (5) by running.

Most of practical heat exchange problems are nonlinear, because thermophysical quantities of equation (1), as well as coefficients of heat transfer and radiation heat exchange in its boundary conditions are functions of required temperature.

Thermal-physical quantities are usually obtained as a result of approximation by temperature functions by corresponding table values.

There are two approaches to solving nonlinear problems. The easiest to implement and economically justified are the so-called quasi-linear difference schemes, in which the desired coefficients of the thermal conductivity equation and

its boundary conditions are calculated depending on the temperature value from the previous time layer. Purely nonlinear schemes, where the coefficients of the heat transfer equation are taken at the temperature values at the new time layer, require iterative methods to construct a convergent iterative process, at each step of which a system of linear equations is solved. In such a formulation, the volume of calculations significantly increases in comparison with the quasi-linear scheme, and the numerical simulation of long technological processes becomes very difficult.

The considered approaches to mathematical modeling of the processes of combined heat exchange are widely used by the authors of the work in the study of thermal regimes of technological equipment

CONCLUSION

The paper presents a method of mathematical modeling of the processes of combined (radiation and convective) heat exchange in technological systems, based on numerical solution of multidimensional differential equation of heat conduction with complex boundary conditions. In this case, the finite-difference approximation of the heat conduction equation and boundary conditions is obtained by the integro-interpolation method (balance method). To solve multidimensional heat exchange problems, a local one-dimensional calculation scheme based on splitting the heat exchange process by spatial variables is used. Due to the known complexity of numerical implementation of heat transfer problems, calculations of complex heat exchange are recommended to be based on the additivity principle, and when recording finite-difference approximation of boundary conditions, it is advisable to use the radiation heat transfer coefficient.

The considered approaches to mathematical modeling of the processes of combined heat exchange can be used in the study of thermal regimes of technological equipment in metallurgy, power engineering, mechanical engineering and other industries, as well as in the training of students of specialized specialties of universities.

Thus, the solution of the fundamental problem of radiative heat transfer in the formulation adopted here (i.e., when a discrete consideration of temperature fields and optical constants is practically possible), ultimately comes down to calculating the angular coefficients (geometric radiation invariants) considered system of surfaces.

REFERENCES

[1] Kukhar, V. V. (2015). Producing of elongated forgings with sharpened end by rupture with local heating of the workpiece method. Metallurgical and Mining Industry, 7(6), 122-132.

[2] N. Hrudkina, L. Aliieva, O. Markov, I. Marchenko, A. Shapoval, P. Abhari, M. Kordenko, "Predicting the shape formation of hollow parts with a flange in the process of combined radial-reverse extrusion," Eastern-European Journal of Enterprise Technologies, vol. 4, no. 1-106, 2020, pp. 55-62.

[3] V. Dragobetskii, M. Zagirnyak, O. Nameumova, S. Shlyk, A. Shapoval, "Method of determination of technological durability of plastically deformed sheet parts of vehicles," International Journal of Engineering and Technology(UAE), vol. 7, no. 4, 2018, pp. 92-99.

[4] O. Markov, V. Kukhar, V. Zlygoriev, A. Shapoval, A. Khvashchynskyi, R. Zhytnikov, "Improvement of Upsetting Process of Four-Beam Workpieces Based on Computerized and Physical Modeling," FME Transactions, vol. 48, no. 4, 2020, pp. 946-953.

[5] V. Dragobetskii, A. Shapoval, D. Mospan, O. Trotsko, V. Lotous, "Excavator bucket teeth strengthening using a plastic explosive deformation," Metallurgical and Mining Industry, vol. 7, no. 4, 2015, pp. 363-368.

[6] S. Soshenko, K. Sizova, V. Perevozniuk, R. Bilous, A. Shmeleva, L. Suprun, "Creative Workspaces of a Modern University in Terms of Student-centered Teaching", Proceedings of the 20th IEEE International Conference on Modern Electrical and Energy Systems, Kremenchuk, Ukraine, 2021, pp. 1-4, DOI: 10.1109/MEES52427.2021.9598535.

[7] O. Markov, A. Khvashchynskyi, A. Musorin, M. Markova, A. Shapoval, N. Hrudkina, "Investigation of new method of large ingots forging based on upsetting of workpieces with ledges", International Journal of Advanced Manufacturing Technology, 122 (3-4), pp. 1383-1394, 2022

[8] V. Dragobetskii, E. Naumova, A. Shapoval, S. Shlyk and D. Moloshtan, "Improving The Operational Reliability Of Stamped Parts Of Electrical Engineering Machines And Electrical Products," 2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2019, pp. 506-509.

[9] I. Savchenko, A. Shapoval, Y. Paleshko, "Simulation of new multilayer waveguides by explosion welding", Defect and Diffusion Forum, 410 DDF, 155-160, 2021

[10] V. Dragobetskii, A. Shapoval, V. Zagoryanskii, "Development of elements of personal protective equipment of new generation on the basis of layered metal compositions," Steel in Translation, Vol. 45 (1), 2015, pp. 33-37.

[11] S. Karnaukh, O. Markov, V. Kukhar, A. Shapoval, "Classification of steels according to their sensitivity to fracture using a synergetic model," International Journal of Advanced Manufacturing Technology, Vol. 119 (7-8) , 2022, pp. 5277-5287.

[12] M. Zagirnyak, V. Zagirnyak, D. Moloshtan, V. Drahobetskyi, A. Shapoval, "A search for technologies implementing a high fighting efficiency of the multilayered elements of military equipment", Eastern-European Journal of Enterprise Technologies, vol. 6, no. 1-102, 2019, pp. 33-40.

[13] M. Zagirnyak, O. Chornyi, V. Nykyforov, O. Sakun, K. Panchenko, K., "Experimental research of electromechanical and biological systems compatibility. [Badania eksperymentalne kompatybilności systemów elektromechanicznych i biologicznych]", *Przeglad Elektrotechniczny*, 92(1), 128-131, 2016, doi:10.15199/48.2016.01.31.

[14] A. Shapoval, I. Savchenko, O. Markov, "Determination coefficient of stress concentration using a conformed display on a circle of a single radius", Solid State Phenomena, 316 SSP, 2021, pp. 928-935.

[15] M. Malovanyy, O. Moroz, S. Hnatush, , O. Maslovska, V. Zhuk, I. Petrushka, V. Nykyforov, A. Sereda, "Perspective technologies of the treatment of the wastewaters with high content of organic pollutants and ammoniacal nitrogen," Journal of Ecological Engineering, vol. 20, no. 2, 2019, pp. 8-15.

[16] V. Kulynych, A. Shapoval, V. Dragobetskii, "Hard alloys recycling as a promising direction of technological equipment for machine-building production," Materials Science Forum, 1052 MSF, 2022, pp. 423-428.

[17] N. Hrudkina, O. Markov, A. Shapoval, V. Titov, I. Aliiev, P. Abhari, K. Malii, "Mathematical and Computer Simulation for the Appearance of Dimple Defect by Cold Combined Extrusion," FME Transactions, Vol. 50 (1) , 2022, pp. 90-98.

[18] S. Gorbatyuk, A. Shapoval, D. Mos'pan, V. Dragobetskii, "Production of periodic bars by vibrational drawing," Steel in Translation, vol. 46, no. 7, 2016, pp. 474-478.

[19] A. Shapoval, D. Mos'Pan, V Dragobetskii, "Ensuring high performance characteristics for explosion-welded bimetals," Metallurgist, vol. 60, no. 3-4, 2016, pp. 313-317.

[20] O. Markov, O. Gerasimenko, L. Aliieva, A. Shapoval, "Development of the metal rheology model of high-temperature deformation for modeling by finite element method", EUREKA, Physics and Engineering, vol. 2, 2019, pp. 52-60.

[21] I. Savchenko, A. Shapoval, I. Kuziev, "Modeling of high module power sources systems safety processes," Materials Science Forum, 1052 MSF, 2022, pp. 399-404.

[22] I. Savchenko, V. Kozechko, A. Shapoval, "Method for Accelerating Diffusion Processes When Borating Structural Steels," Lecture Notes in Mechanical Engineering, 2022, pp. 793-800.

V. Kukhar, O. Kurpe, E. Klimov, E. Balalayeva, V. Dragobetskii, "Improvement of the method for calculating the metal temperature loss on a Coilbox unit at the rolling on hot strip mills", International Journal of Engineering and Technology(UAE), vol. 7, no. 4, pp. 35-39, 2018, doi:10.14419/ijet.v7i4.3.19548.