Decision-making support when determining the heating systems parameters for hydraulic presses

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Abstract. The problem formulation for decision-making support during determining the parameters of the heating systems for hydraulic presses and its decomposition, based on the optimization problem of elements of the heating system, mathematical models of the functioning of the heating systems elements of hydraulic presses, is proposed. The structure of the decision-making support system for the parameters determination of the heating systems of hydraulic presses, the functions of its elements, information flows between them is determined. The information models for the information storage and processing on the initial data and the results of solved problems are developed.

1. Introduction
The application area of hydraulic presses, carrying out the temperature processing of loaded products, covers the production of mechanical rubber goods (MRG), fibreboards, composite materials and plastic products by hot pressing method [1 - 4]. Moreover, the hydraulic presses are in demand in the production of high-precision metal products in technological operations of loose issue and isothermal stamping [5, 6]. The greatest attention in the design and operation of press equipment is given to the heating system, the elements of which are heating plates and heaters, molds and heat insulation plates that separate the heating plates from the supporting structural elements (table, frame or beam).

An analysis of scientific publications on decision-making problems in the design and operation of press equipment, see [7-10], leads to the conclusion that the existing approaches are focused mainly on the processes of stamping and the development of press tools, and almost no attention is paid to decision-making for defining the heating systems parameters.

2. Problem formulation
The parameters determination for the hydraulic press heating system involves making the following decisions:
1) selection of a heating method for press plates (such as heaters): steam, ohmic or induction;
2) determination of the required number, power of heaters, their configuration and location in the plate;
3) determination of the processed products position (molds with products) on the working surface of the heating plate;
4) selection of materials and determination of the necessary thicknesses of insulation plates that protect the supporting elements of the press structure (table, top-end transverse member or cross beam) from high temperatures.
The selection of the method of plates heating is limited by setting the processing temperatures of the products: the use of steam heating at temperatures above 200°C and induction heating above 250°C is difficult.

The number \((n_h)\), power \((Q_h)\), configuration and position of heaters should provide the required heating rate (achievement of the operating temperature \(T_z\) at the installation site of the control thermocouple in a given time \(\tau_z\)) and the degree of uniformity of the temperature plate field (the deviation of the minimum and maximum temperatures from \(T_z\) does not exceed the specified value \(\Delta T_p\)).

The sum of \(Q_h\) values should not exceed the specified maximum power of the heating plate \((Q_{max})\).

The configuration of steam channels and tubular electric heaters (TEH) is determined by the number, diameter \((d_h)\) of channels or holes for TEH, the distance between their axes \((h_{hi}, i = 1, ..., n_n - 1)\). The shape and sizes of the inductors are usually determined by the standards of a particular enterprise, and their location in the volume of the heating plate is limited by the minimum distances between the grooves of adjacent heaters, the groove of the heater and the boundary of the working surface of the plate. The configuration of spiral heaters is determined by the minimum allowable bend radius of the axis of the spiral, the allowable temperature difference at the places of bends, and the location, similar to inductors, by the distances between the grooves of adjacent spirals, the groove and the boundary of the working surface of the plate.

The position of products of a set shape and size (molds of assigned design with products placed in them) is determined by the sizes of the working surface of the heating plate and the required degree of uniformity of the temperature field in the size of the product during the period \((\tau_f)\) of its processing: the deviation of the minimum and maximum temperatures from the given \((T_f)\) should not exceed the specified value \(\Delta T_f\). The temperature fields of the products also depend on the chosen method of stabilizing the temperature of the heating plates.

The selection of materials \((m_{ins})\) and determination of the required thickness of the insulation plates \((h_{ins})\) is defined by the maximum temperatures of the heating plates and the distance \((H)\) from the top-end transverse member (beam) of the press to the lowered table. The average temperature of the thermal insulation surface in contact with the press structural elements should not exceed a determined value \((T_{ins})\), and the sum of the distances between the extended heating plates and the sum of the heights of the heating plates and thermal insulation plates should not exceed \(H\). In addition, it is necessary to control the temperature values between the layers of thermal insulation from various materials: they should not exceed the maximum permissible numbers for the outer layer.

It is proposed to use the amount of depreciation of its cost and operating costs associated with its energy intensity (energy costs from the beginning to the end of processing one batch of products) as a criterion for the optimality of a developed or reconstructed system for heating a hydraulic press, for the period of that products release.

Thus, the problem of parameters determination for the heating system of a hydraulic press can be formulated as follows: select the type, determine the number, power of the heaters, their configuration and location in the size of the plate, determine the position of the processed products on the working surface of the heating plate, select the material and thickness of the insulation plates, ensuring the fulfillment of all the above restrictions and a minimum amount of capital and operating costs for the system.

Decision-making support in the development of a heating system for a hydraulic press provides for the determination and analysis of temperature fields of heating plates and heaters, molds and processed products during heating, stabilization of temperature fields during products processing, determination and analysis of average temperatures on the external surfaces of all thermal insulation boards made from different materials.

### 3. Problem decomposition

Obviously, the solution of the formulated problem, taking into account the need for the formation and analysis of the temperature fields of the heating system elements, will require significant computing resources and time consumption. Therefore, it is proposed to decompose it into three local problems:

- problem A1 of heating method selection and determination of heating plate design;
- problem A2 of placement of processed products on the working surface of heating plate, considering the method of its temperature controlling;
- problem A3 of materials selection and determination of insulation plates thicknesses.

The A1 problem statement provides for the selection of type \((t_h)\) and number \((n_h)\), determination of heaters power \((Q_h)\), their configurations and location in plate’s size \((X_h)\), ensuring a minimum of the depreciation of the plate cost \((S_p)\) and the energy cost \((E_p)\) spent for the processing of any products during the period of their release

\[
t_h^*, n_h^*, Q_h^* = \text{argmin}\left[ S_p(t_h, n_h, Q_h, X_h) + E_p(t_h, n_h, Q_h, X_h) \right]
\]

with links

\[
T(x, y, z, \tau) = \Omega(T_0; n_h, N_h, q_h, Q_h, X_h, i = 1, ..., n_h; \tau)
\]

and restrictions:

\[
X_{hi} \in [X_{hi}, X_{hi}^*], i = 1, ..., n_h
\]

\[
\sum_{i=1}^{n_h} Q_{hi} \leq Q_{\text{max}}
\]

\[
V_i \cap V_j = \emptyset, i, j = 1, ..., n_h, i \neq j
\]

\[
\max \left\{ T(x, y, u, \tau) \right\} - T_s \leq \Delta T_p, \quad T_s - \min \left\{ T(x, y, u, \tau) \right\} \leq \Delta T_p
\]

Here, the function \(\Omega\) represents a solution to the differential equation of unsteady heat conduction in a plate with internal heat sources. Initial condition for its solution:

\[
T(x, y, z, 0) = T_0
\]

and the type of boundary conditions (BC) is determined by the conditions of heat removal into the structural elements of the press and the environment; \(Q_h = (Q_{h1}, ..., Q_{h_{n_h}})\) is the vector of heaters power; \(X_h = (X_{h1}, ..., X_{h_{n_h}})\) is the matrix of structural parameters of heaters; \(X_{hi}\) is the vector of parameters of \(i\) heater, for example, for a rectangular inductor \(X_{hi} = (l_{hi}, s_{hi}, x_{chi}, y_{chi})\); \(l_{hi}, s_{hi}\) - length and width of the projection of \(i\) inductor on the working surface of the plate; \(x_{chi}, y_{chi}\) - coordinates of the center of \(i\) inductor relative to the lower left corner of the plate; \(\Delta p\) is the distance from the edge of the plate to the border of its working surface (~ 25 mm); \(\tau_s\) – the duration of the stabilization period of the temperature fields of heating system elements; \(T(x, y, z, \tau)\) is the temperature at the point \((x, y, z)\) of the plate at time \(\tau\); \(u = 0\) if the bottom surface of the plate is working and \(u = h\) (plate’s height) if the top; \(q_{hi}\) is the specific heat in the groove \(v_{hi}\) under \(i\) heater; \(V_i\) is the groove volume of \(i\) heater and the area, including the minimum allowable distances between the grooves of adjacent heaters, the groove of heater and boundaries of plate’s working surface; \(T_s\) is the temperature at the placing of the control thermocouple; \(T_0\) is the environment temperature.

The A2 problem consists of the determination of the coordinates \((x_{fj}, y_{fj}, j = 1, ..., n_f)\) of the center (or some other point) of the projection of each product (mold with product) on the working surface of the heating plate, minimizing the temperature difference over the products batch in non-stationary mode of their processing

\[
\max_{j=1, ..., n_f} \left\{ \max_{x_{fj}, y_{fj}} \left\{ T_{ij}(x, y, z, \tau) \right\} - \min_{x_{fj}, y_{fj}} \left\{ T_{ij}(x, y, z, \tau) \right\} \right\} \rightarrow \min_{x_{fj}, y_{fj}, j=1, ..., n_f}
\]
with links:

\[ T_j(x, y, z, \tau) = \Theta(T_0, T(x, y, \tau), u = 0, h; x_j, y_j), \quad j = 1, \ldots, n_f \]  

(8)

and restrictions:

\[
\max_{x_j \in [x_j], \tau \in [\tau]} \left\{ T_j(x, y, z, \tau) \right\} - T_f \leq \Delta T_f, \quad T_f = \min_{x_j \in [x_j], \tau \in [\tau]} \left\{ T_j(x, y, z, \tau) \right\} \leq \Delta T_f, \quad j = 1, \ldots, n_f
\]

(9)

Here, the function \( \Theta \) represents the solution of the system of differential equations of non-stationary heat conductivity for all plates and products (molds with products) with boundary conditions (BC) of the fourth kind; \( n_a \) is the number of products processed simultaneously; \( V_j \) is the matrix of boundary values of the coordinates of the volume of \( j \) product; \( \tau \) - the moment of the end of processing of products batch; \( T_j(x, y, z, \tau) \), \( \bar{T}(x, y, u, \tau) \) is the temperature field of \( j \) product, the upper \((u = 0)\) and lower \((u = h)\) heating plates at time \( \tau \).

Problem \( A_3 \) is the problem of package formation of \( n_{ins} \) heat-insulating plates: select materials \( M_{ins} \) and determine the values of their thicknesses \( H_{ins} \), ensuring a minimum depreciation of the cost of \( S_{ins} \) package for the period for which problem \( A_1 \) is solved:

\[ M^{*}_{ins}, H^{*}_{ins} = \text{argmin}\{S_{ins}(M_{ins}, H_{ins})\} \]

(10)

with conditions:

\[ h_p(n_p - 1) + h_n n_p + h_{ins} n_{ins} \leq H \]

(11)

\[ T_{bk} \leq T_{bk+1}, \quad k = 1, \ldots, n_{ins} - 2; \quad T_b \leq T_{ins} \]

(12)

where \( M_{ins} = (m_{ins1}, \ldots, m_{ins_{ins}}) \), \( H_{ins} = (h_{ins1}, \ldots, h_{ins_{ins}}) \) – vectors of materials and thicknesses of insulation plates; \( n_p \) is the number of heating plates in the press; \( h_p \) is the distance between the extended heating plates; \( T_{bk}, T_{bk+1}, T_b \) is the average temperature of the outer surface of \( k \) heat insulation plate, the maximum allowable temperature for the material of \((k + 1)\) plate and the average temperature of the outer surface of the heat-insulation plate package.

In order to determine the values \( T_{bk} \) and \( T_b \), it is necessary to solve the non-stationary heat conduction equations for the lower or upper heating plate and the package of thermal insulation plates. For the end surfaces of thermal insulation plates and the working surface of the heating plate, you can use BC of the third kind, calculating the values of heat transfer coefficients according to well-known criteria equations. On the surfaces of thermal insulation in contact with the structural elements of the press, a fourth-order BC should be used, however, the contact is not ideal: there are stiffeners on the surface of the press table, and on the surface of the top-end transverse member or crosshead there are projections of a rectangular cross section.

It is proposed to simulate the influence of press structural elements on thermal processes in the calculation system (heating plates, molds, products, heat-insulating plates) by boundary conditions of the third kind, approximately calculating the heat transfer coefficient based on experimental data. Such fictitious heat transfer coefficient characterizes the entire structure of the press and external conditions and does not depend on the thicknesses and materials of the insulation plates.

4. Structure DMSS by determining the heating systems parameters for hydraulic presses

Information flows between problems \( A_1, A_2 \) and \( A_3 \) are presented in figure 1. In this figure:

\( C_1, C_2, C_3 \) – regulatory documents used in calculating the temperature fields of the press heating plates, products during their processing and the temperatures of the insulation plates surfaces; \( I_1 \) - results of \( A_1 \) problem solution: type, number and power of the heating elements of the press plate, their configuration and location, the temperature field of the plate at the end of the periods of heating and stabilization, temperature drops along the working surface of the plate; \( I_2 \) - results of \( A_2 \) problem solution: temperature drop in a batch of products in a stationary mode of processing, parameters for the temperatures stabilization of the working surfaces of plates; \( I_3 \) - results of \( A_3 \) problem solution: average temperatures of the outer surfaces of insulation plates; \( I_2^b \) - information about the problems of ensuring a set temperature for products during processing (insufficient durations of heating and
stabilization periods, too large temperature differences in the volume of some products); $P_3^b$ - problems of thermal insulation elements (too much thickness, raised temperature of external surfaces).

**Figure 1.** Information flows between development problems heating hydraulic press system.

Problems $A_1$, $A_2$ and $A_3$ can be determined as follows:

$A_1 : t_c \cup f_2^0 \cup f_3^0 \rightarrow \text{MM}_1, \text{IM}_1 \rightarrow I_1 , A_2 : t_c \cup f_1 \rightarrow \text{MM}_2, \text{IM}_2 \rightarrow I_2 , A_3 : t_c \cup f_1 \rightarrow \text{MM}_3, \text{IM}_3 \rightarrow I_3 ,$

where $\text{MM}_1$ – mathematical model of the heating process, the construction of the heating plate; $\text{MM}_2$ – mathematical model of the temperature fields of products during their processing, considering the method of the temperature stabilization of heating plates; $\text{MM}_3$ – mathematical model of thermal processes in thermal insulation plates; $\text{IM}_1 \ IM_2 IM_3$ – corresponding information models.

The structure of the decision-making support system (DMSS) for the determination of the heating systems parameters for hydraulic presses is developed based on figure 1 and is presented in figure 2.

The control program independently calls the necessary module, or makes it possible for the decision maker (DM) to do this. The decision maker evaluates the results of the modules for solving problems $A_1$, $A_2$ and $A_3$, has the ability to adjust the source data to solve them and restart the modules for problems solution. The reasons for adjusting the source data may be:

- situations when this or that problem has no solutions (too severe restrictions on temperature drops for the working surfaces of heating plates and products, permissible temperatures of structural elements protected by thermal insulation);

- lack of practical implementation of the obtained solutions (too complicated geometry of the grooves to accommodate the heaters, difficulties in acquiring the recommended materials of the heating plates and thermal insulation).

In addition to modules for $A_1$, $A_2$ and $A_3$ problems solution, DMSS contains a service module that is designed to support information storage, user registration, distribution of access rights to information, as well as the module for 3D models construction of the press heating system elements.
Each of problems $A_1, A_2, A_3$ has a set of initial data $X \in XV$ and a set of results for solution $Y \subseteq YV$, where $XV$ and $YV$ are sets of possible values for $X$ and $Y$. In turn, $XV \subseteq DX$ and $YV \subseteq DY$, where $DX$, $DY$ are sets (intervals) of possible values of $X$ and $Y$. For example, an indication of the plate’s material is part of the source data ($X$). The set $XV$ is a list of steel types that meet the requirements of the technical specifications, and $DX$ is the set of all steel types used in the presses’ development. Thus, any of the above information models can be represented as a tuple:

$$IM = <X, Y, DX, DY, IZ>,$$

where $X$ is a list of initial data necessary to solve the corresponding problem; $Y$ - list of the results of its solution; $DX$ - set of possible values of the source data (information necessary to solve the problem); $DY$ - set of possible values of the results of problem solution; $IZ$ - additional information that is required in the process of problem solution.

We note that $X$ and $Y$ are not source data, but only a list of source data (structure). Information is entered in $X$ and $Y$ in the process of a specific problem solution. The sets $DX$, $DY$, $IZ$, unlike $X$ and $Y$, contain both the structure and the information itself, which is entered before the problem solution, or rather, can be entered and updated continuously (the process of providing information support).

5. Mathematical and Information Models
Mathematical models $MM1$, $MM2$, $MM3$ in addition to relations (2)-(5), (7)-(9) and (10)-(11), include the equations for determining specific heat emissions during steam, ohmic and induction heating of plates [11], the minimum allowable bending radius of the spiral ohmic heater [12], the internal heat generation of the inductors during stabilization of the temperature of the heating plates [13], and the average surface temperatures of the insulation plates [14].

As an example of the information model, we consider $IM1$ model. The list of source data necessary to solve problem $A1$ includes the following information.

1. The subset of the technical specification for the press design

$$tz_1 = \{l, s, h, h_c, \Delta p, \delta h, Q_p, T_z, \Delta T_p, T_{ds}, T_u, \Delta \tau_u\} \subseteq tz,$$
where \( l \) - plate length (m), \( s \) - width (m), \( h \) - height (m), \( h_c \) - cover height (m), \( \Delta p \) - width of edges that are not included in the working surface (m), \( \delta_s \) - minimum distance between grooves under heaters and steam channels (m), \( Q_p \) - plate power (W), \( T_z \) - operating temperature (°C), \( \tau_z \) - required rate of heating the plate from initial to operating temperature (s), \( \Delta T_p \) - permissible temperature difference along the working surface of the plate at the end of heating period and during the stabilization period (°C), \( T_a \), \( T_u \) - lower and upper limits of positioner’s operation (°C), \( \Delta \tau \) - minimum update period of the control signal of temperature controller (s).

The elements of \( D_1 \) subset are interval, for example, \( s_{\text{min}} < s < s_{\text{max}} \), where \( s_{\text{min}}, s_{\text{max}} \) are the minimum and maximum possible values of \( s \). We denote the interval \([s_{\text{min}}, s_{\text{max}}]\) as \([s]\). Considering such notations, the set of possible values of the elements of subset \( D_1 \) represents

\[
D_{1} = \{([l], [s], [h]), [\Delta p], [\delta_s], [Q_p], [T_z], [\tau_z], [\Delta T_p], [T_a], [T_u], [\Delta \tau] \}.
\]

2. The set of characteristics of the plate material

\[
hp = \{m_p, \rho, c, \lambda\},
\]

where \( m_p \) - model of material (steel or alloy designation), \( \rho \) - density (kg/m³), \( c \) - specific heat (J/kg/K), \( \lambda \) - coefficient of thermal conductivity of the plate material (W/m/K).

Considering the interval format of the elements of \( hp \) set, we represent the set of values of the plate material characteristics as

\[
Dhp = \{M, [p], [c], [\lambda]\},
\]

where \( M = \{m_{\text{shk}}, k=1,...,K1\} \) - set of ferromagnetic steels types used for manufacturing of heating plates for hydraulic presses.

3. The set of heaters characteristics

\[
hn = \{m_h, d_h, s_h, U_h, P_h, f_h, l_h, s_h\},
\]

where \( m_h \) - wire material of inductors or ohmic spirals (material or alloy designation), \( d_h \) - wire diameter (m), \( s_h \) - insulation thickness (m), \( U_h \) - operating voltage of inductors, ohmic spirals (V), \( P_h \) - working pressure of heating steam (Pa), \( f_h \) - index of the shape of steam channels: vertical (perpendicular to the length) or horizontal (parallel to the length), \( l_h, s_h \) - length and width of typical inductors (m).

The set of possible heater characteristics

\[
Dhn = \{MS_h, DH_h, [Sl], [U_h], [P_h], FH, LH, SH\},
\]

where \( MS_h = \{m_{\text{shk}}, k=1,...,K2\} \) - set of material types used for manufacturing of wire induction or ohmic heaters; \( DH = \{d_{\text{shk}}, k=1,...,K3\} \) - set of possible diameters of wire, \( FH = \{f_{\text{shk}}, k=4=1,...,K4\} \) - set of possible forms of steam channels, \( LH = \{l_{\text{shk}}, k=5=1,...,K5\}, SH = \{s_{\text{shk}}, k=6=1,...,K6\} \) - set of possible values of length and width of typical inductors.

The set of results of \( A1 \) problem solution:

\[
R1 = \{v_h, n_h, Q_h, \Delta L, XY_h, 2D, T_p, \Delta T_p, \tau_p, E_p\},
\]

where \( v_h \) - indicator of the heating type (steam, ohmic, induction), \( n_h \) - number of heaters, \( Q_h = Q_{hi}, i = 1,...,n_h \) - their power (W), \( \Delta L = \Delta l_i, i = 1,...,n_h - 1 \) - distance between the axes of the steam channels, \( XY_h = x_{hi}, y_{hi}, i = 1,...,n_h \) - coordinates of the symmetry centers of inductors on plate’s working surface (m), 2D - 2D-models of grooves for ohmic spirals, \( T_p \) - average temperature of the working surface of plate at the end of heating period and during the stabilization period (°C), \( \Delta T_p \) - temperature difference on the working surface at the end of heating period and during the stabilization period (°C), \( \tau_p \) - the duration of plate heating period (s), \( E_p \) - total energy intensity of plate (J) during its heating and stabilization of the operating temperature.

The set of possible values of results

\[
DR1 = \{[v_h], [n_h], [T_p], [\tau_p], [\Delta T_p], [E_p], [Q_h], [\Delta L], [x_{hi}], [y_{hi}]\}.
\]
Thus, the information model for selection of the heating method and determination of the heating plate construction is written as follows

\[ IM1=<(tz_1, hp, hn, R1, Dtz1, Dhp, Dhn, DR1)> \]

The database tables are based on the analysis of information models: the types of characteristics of the press elements and the types of sets of acceptable values of the characteristics are selected.

The elements of the developed DMSS in determination of the heating systems' parameters for hydraulic presses were used to perform calculations of industrial presses for orders of JSC “Tambovpolymermash Plant” and JSC “ARTI-Zavod”, Tambov.

6. Conclusions

The problem formulation for decision-making support in determining the parameters of the heating systems for hydraulic presses and its decomposition into the problems of optimization of the heating system elements, the mathematical model of the functioning of heating systems elements of hydraulic presses are proposed.

The structure of DMSS is determined when defining the parameters of the heating systems for hydraulic presses, the functions of its elements, information flows between them.

The information models were developed for information storage and processing about the initial data and the results of problems solution of optimizing the elements for heating systems of hydraulic presses, including the values of characteristics of elements and intervals of their possible values.

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