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OPTIMIZATION OF REFRACTORY WALL STRUCTURES

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Summary

One of the main motivating factors of industrial reconstruction is the decrease of energy consumption and the increase of energy efficiency.
The economical operation of industrial furnaces depends on many factors. One of them is the structure of the wall. The adaptation of structural optimisation widely applied in machine industry for the planning of refractory wall structures can contribute to the structural rationalisation of industrial furnaces.
The expert system under elaboration is developed within the frame of the subprogram of research activity numbered by OTKA 4407.

Zusammenfassung

Wichtige Faktoren der Konstruktionsumformierung in der Industrie sind die Reduktion des Energieaufwandes und die Steigerung der Energiewirksamkeit.
Der rationelle wirtschaftliche Betrieb der industriellen von mehreren Faktoren hängt Öfen ab. Einer der diesen Faktoren ist die Konstruktion der Wandung. Die in der Maschinenindustrie verbreitet verwandte Konstruktionsoptimierungs-Adaptierung zum Entwurf der brandfesten Wandkonstruktionen ist zu strukturellen Rationalisierung der industriellen Öfen beizutragen.

Das Expertsystem, das in der Ausarbeitung steht, wird im Rahmen eines Unterprogrammes der Forschungstätigkeit Nummer: OTKA 4407 ausgearbeitet.

The economical situation of our country depends to a large extent on the successful operation of the industry. For the successful operation the reconstruction of the industry is mainly necessary, whose motive factors are the decrease of power consumption and the increase of energy efficiency. It can be realised by structures whose size and applied materials are designed by means of optimisation.

The economical operation of industrial furnaces is a function of several factors. One of them is the wall which is the most expensive. This fact gives reason for that the structure optimisation widely applied in machine design is used for planning refractory wall structures. The precondition of optimisation is that wide choice of refractory and heat insulating furnace materials must be available with required application technic and costs. So main task is to process the necessary data of wide choice of these materials in a form suitable for computer.

Different refractory materials consist of grains and fibers of different size, composition and quality as well as contain pores of different size and volume. The bond keeps grains and fibers together, which can be - regarding its feature - hydraulic, chemical, organic or ceramic. These together determine properties of refractory products, so to know of following characteristics is very important [1,2]:

- mineral, chemical composition - it can be basic or acid, so it helps us to conclude the quality of grains (fibers);
- grain size - it influences the strength, solidity, heat conductivity and mode of building;
- opening porosity - it is very important as regarding strength, heat conductivity and gas permittivity, and it shows the ratio of pores volume and the total volume in %.

Choosing physical properties there are also to be known:
- maximum applicable temperature, limit temperature;
- specific heat capacity - a number of heat storage capacity of refractory materials;
- heat conductivity - it is necessary for the economical operation and avoiding accidents;
- cold crushing strength - showing the resistivity to mechanical strains, as a general rule the bending and tensile strength are its 10-22%;
- softening under loading - in examining the resistance fire the test piece bends due its own weight, but in practice the wall is under stresses. this characteristics means the temperature at which the test piece is pressed together with its 40 % under constant load;
- density or material need - gives the amount of material required for making wall of unit volume;
- coefficient of thermal expansion, shrinkage at limit temperature - property connecting to size change due to heating and resistance to heat fluctuation, but it is important in forming compensation joint as well as determining optimum heating and cooling speed of the wall.

On the base of the above mentioned characteristics further information is required about the material which concerns purchase (name, address, phone and fax of the producer) and given building technology. It is expedient to record applications and specialities recommended by the producer.

All of these have been considered during setting the data base up corresponding the fact that different characteristics come into the limelight in case of different materials. On the base of this thinking different data bases are available for bricks, masses and fiber materials. The information content is similar but it reflects differences too.

Now the data base contains above mentioned data of more than 300 refractory and heat insulating materials. The appearance of new materials and aspects of optimisation offer motives for extending the data base constantly.

The optimisation of the wall means the searching of cost minimum. Two costs are to be considered in the wall relation [3,4]:
- cost of building, which depends on the price of applied material and the cost of realisation;
- cost of energy transferred to the environment through the wall of the operating furnace and stored in the wall depending on operation mode.

A function (objective function) is to created for optimisation, whose extreme value gives the optimum. In our case - assuming continuous operation of the furnace - it can be described as follows:

$$K = \sum_{i=1}^{n} \frac{x_i\,(P_i + L_i)}{t_a} + \varphi \cdot t_{ann.} \cdot P_{fuel} \frac{3600}{Hu} \quad \left[\frac{Ft}{year}\right]$$

where: K - specific annual cost of the unit surface of the furnace wall;
n - number of wall layers;
x_i - thickness of the layer i, [m];
P_i - price of the material of the layer i, [Ft/m^3];
L_i - forming cost of the layer i, [Ft/m^3];
t_a - amortisation time of the furnace, [year];
t_{ann} - annual operating time of the furnace, [h];
P_{fuel} - price of the fuel, [Ft/m^3];
Hu - heating value of the fuel, [J/m^3];

$$\varphi = \frac{T_{fb} - T_k}{\sum_{i=1}^{n} \frac{x_i}{\lambda_i} + \frac{1}{\alpha_k}} \quad \left[\frac{W}{m^2}\right]$$

where: T_{fb} - inner surface temperature of the furnace wall, [°C];
T_k - temperature of the environment, [°C];
α_k - heat transfer coefficient between the environment and furnace wall, [W/m^2 °C];
$\lambda_i = f(T_i)$ - heat conductivity of the layer 'i' as a function of mean temperature of the layer, [W/m °C].

To find the optimum of the above mentioned cost function three algorithms - worked in the practice of structure optimisation - have been used.

Optimization technique of the wall structure

The different single- and multiobjective optimization techniques makes the designer able to determine the optimal sizes of structures, to get the best solution among several alternatives. The efficiencies of these mathematical programming techniques (MP) are different.

The general formulation of a single-criterion nonlinear programming problem is the following:

$$\begin{array}{lll} \text{minimize} & f(x), & x = x_1, x_2, .., x_N, \\ \text{subject to} & g_j(x) \leq 0, & j = 1,2,.....,P, \\ & h_k(x) = 0, & k = P+1,...,P+M. \qquad (1) \end{array}$$

The Hillclimb algorithm [5]

The procedure is based on the "automatic" method proposed by Rosenbrock [4]. The method of rotating coordinates can be considered as a further development of the Hooke and Jeeves method. Before starting the minimization process, define a set of 'initial' step lengths S_i, to be taken along the search directions M_i, i= 1,2,...,N. The starting point must satisfies the constraints and does not lie in the boundary zones. The boundary zones are defined as follows:

$$\begin{array}{ll} \text{lower zone:} & x_i^L \leq x_i \leq x_i^L + (x_i^U - x_i^L) * 10^{-4} \\ \text{upper zone:} & x_i^U \leq x_i \leq x_i^U - (x_i^U - x_i^L) * 10^{-4} \qquad i = 1,2,..,M \end{array}$$

The variables are stepped a distance S_i parallel to the axis and the function is evaluated.

$$\text{new } x_i^{(k)} = \text{old } x_i^{(k)} + S_j^{(k)} * M_{i,j}^{(k)}$$

If the current point objective function value is worse, than the previous good value, or if the constraints are violated, the trial point is a failure and S_i decreased by a factor μ, $0 < \mu \leq 1.0$ and the direction of movement reversed. If the move is termed a success, S_i increased by a factor ß, $ß \leq 1.0$. The new point is retained and a success is recorded. The values of μ and ß are usually taken as 3.0 and 0.5 respectively. If the current point lies within a boundary zone, the objective function is modified by the distance into the boundary zone.

At the algorithm, the coordinate system is rotated in each stage of minimization. The procedure stops if the convergence criterion or the iteration limit is reached. No derivatives are required. The procedure is very quick, but it gives usually local optima, so it is advisable to use more starting points. The flow chart of the program is enclosed.

Objective function: $y = f(x_1, x_2, \ldots, x_N)$

Design constraints: $G_k \leq x_k \leq H_k$ $k = 1,2,\ldots,N$ explicit variables

$k = N+1,\ldots,M$ implicit variables

Boundary zone: $G_k \leq x_k \leq (G_k + (H_k - G_k)\,10^{-4})$; lower zone

$x_k \leq x_k \leq (H_k - (H_k - G_k)\,10^{-4})$; upper zone

Modification of objective function:

$$f(new) = f(old) - (f(old) - f^*)(3L - 4L^2 + 2L^3)$$

L = distance into boundary zone/ width of boundary zone

$$L = \frac{x_i^L + (x_i^U - x_i^L)10^{-4} - x_i}{(x_i^U - x_i^L)10^{-4}};\quad \text{lower zone}$$

$$L = \frac{X_i - (X_i^U - (X_i^U - X_i^L)10^{-4})}{(X_i^U - X_i^L)10^{-4}}; \quad \text{upper zone}$$

At the inner edge of the zone L = 0 thus f(new) = f(old) at the constraints L = 1 thus f(new) = f*

The search is terminated , when the convergence criteria is satisfied (see the flow chart).

The Hillclimb algorithm is very useful for technical computations, it can find both unrounded and discrete values and the efficiency is good [6,7].

In our calculation performed in the foregoing [1,2] conditions applied for the aim function are to be changed according to our experiences by considering the follows:

- Among the temperature limits in the foregoing only the maximum of the external surface temperature was prescribed, but from theoretical and practical views the applicable temperature range is to be also considered.

- Because of the manifold iteration the use of the algorithm applying the combinatorial model seems to be efficient among the mentioned optimum searching process, so that it will be further used.

- In former calculation only forgiven combinations of refractory and insulating material were investigated in absence of computerised data base. By having this the choice from materials available in the data base shall be connected to the optimisation on the base of technological and technical application aspects.

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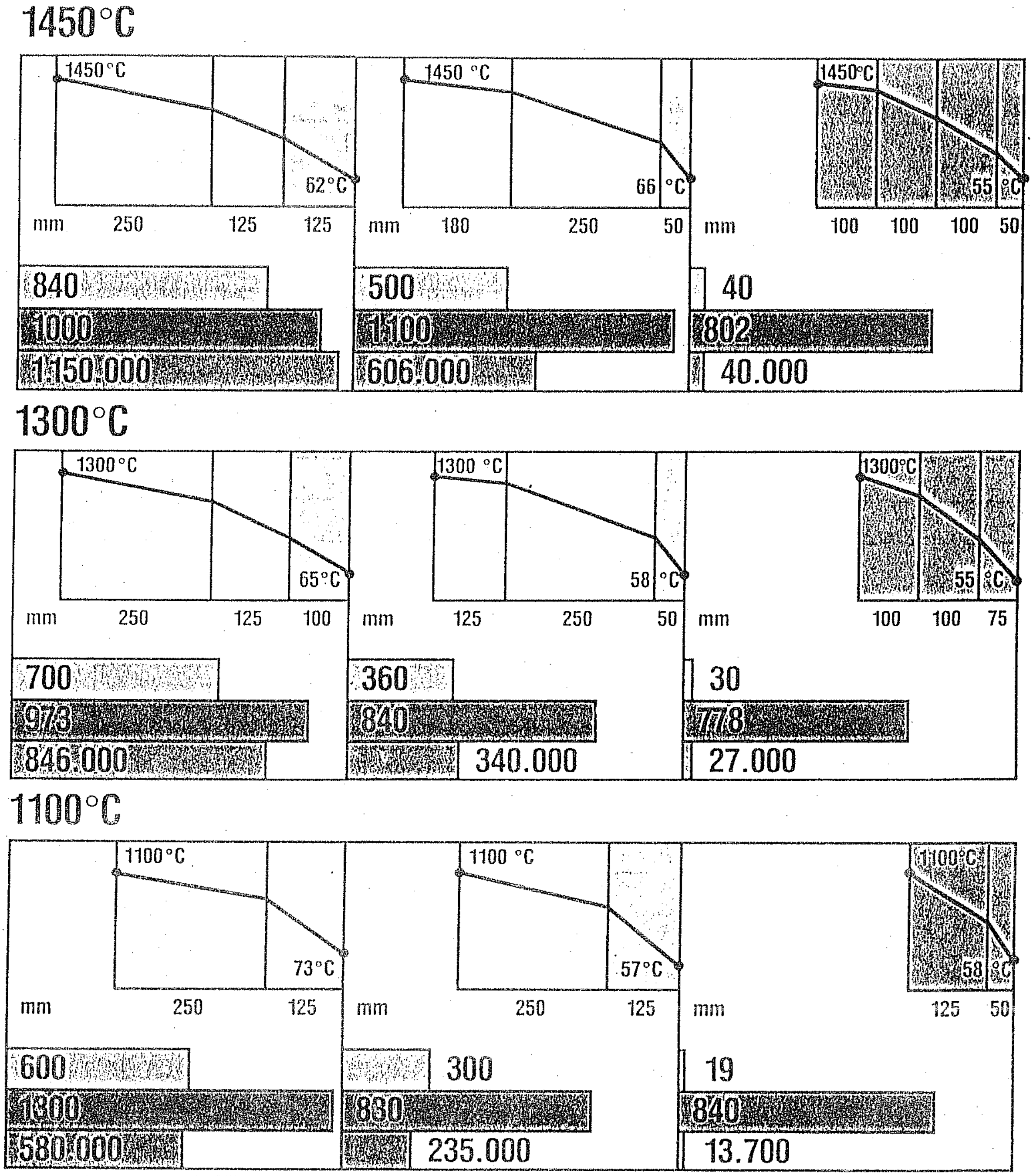


SOLID CHAMOTTE BRICKS

LIGHT WEIGHT FIREBRICKS

INSULATING FIREBRICKS

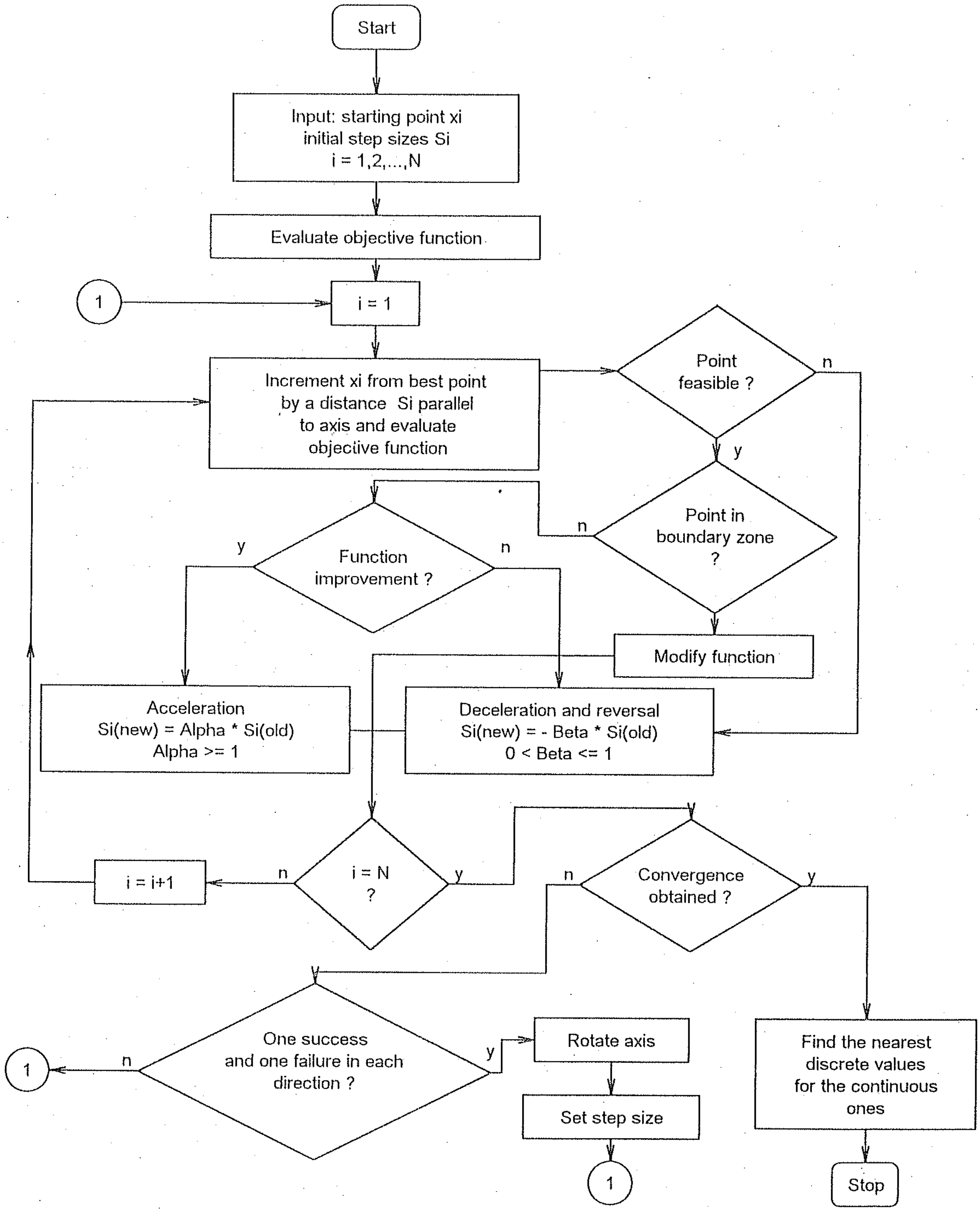
CERAMICS FIBROUS

MINERAL FIBROUS

WEIGHT OF THE WALL (kg/m2)

WAS LOSS (kJ/m2)

HEAT CAPACITY (kJ/m2)



Flow chart of the Hillclimb procedure