On the Calculation of the Boiler Thermal Diagram

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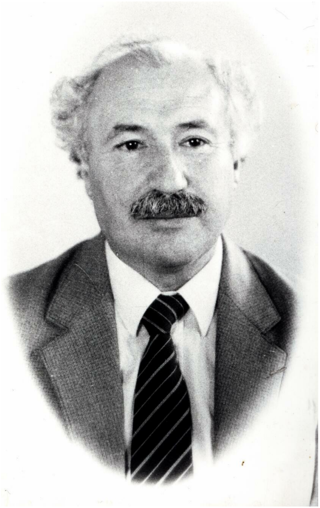
Naum Zuselevich Shor



Academician Naum Zuselevich Shor (1937 - 2006)

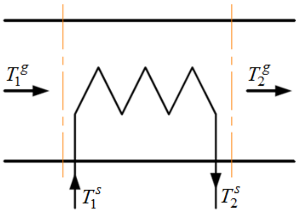
Optimal Design Problem

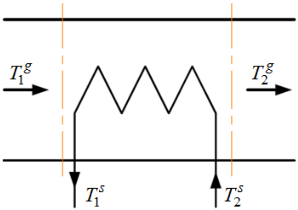
Founded by academician N.Z. Shor department of non-smooth optimization methods is known not only for the original algorithms developed, but also for the experience in using them for a wide range of applied problems. We present a brief description of one of these problems related with the design of separate elements of steam boilers.

The work was carried out jointly with specialists from the Kharkov Central Design Bureau "Energoprogress".

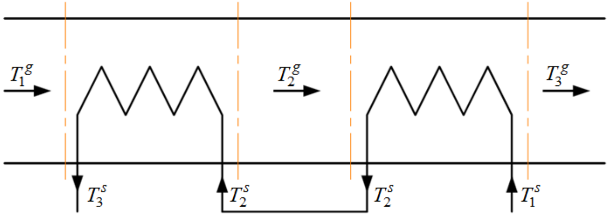
The main element of the thermal scheme is a heat exchanger, a special technical device in which thermal energy is transfered to water vapor. The heat exchanger is placed in the gas path of the boiler, which we will represent as a kind of converter (“black box”), which has two inputs and two outputs. One of the inputs (one of the outputs) is determined by the physical parameters of the gas flow, the second – by steam.

Heat exchanger





Scheme



Optimal Design Problem

Let $T_1^g, T_2^g, (T_1^s, T_2^s)$ be the inlet gas (steam) temperatures and heat exchanger outlet. Calculation the output temperatures T_2^g, T_2^s is a rather complex problem of mathematical physics. In thermal engineering, special methods for approximate solution of this problem have been developed for such calculations. As a rule, the algorithm for such calculations requires solving a system of nonlinear equations. In problems of choosing the design parameters of heat exchangers, it is necessary to carry out repeated calculations of the thermal scheme (tens of thousands of times). In this work, an algorithm for calculating the thermal scheme is proposed, based on the idea of introducing a model heat exchanger.

Model Heat Exchanger

The following conditions are met for heat exchangers: $T_2^g \in [T_1^s, T_1^g]$, $T_2^s \in [T_1^s, T_1^g]$. When transferring thermal energy without using conversion to other types of energy, the fulfillment of these relationships is obvious from thermodynamic considerations. The specified conditions are equivalent to the relations:

$$T_2^g = \lambda^g T_1^g + (1 - \lambda^g) T_1^s, \qquad (1)$$

$$T_2^s = (1 - \lambda^s) T_1^g + \lambda^s T_1^s, \qquad (2)$$

where

$$0 \leq \lambda^g \leq 1, 0 \leq \lambda^s \leq 1. \qquad (3)$$

Model Heat Exchanger

Constants λ^g, λ^s are defined as follows. For given input temperatures $\tilde{T}_1^g, \tilde{T}_1^s$,$\tilde{T}_1^g \neq \tilde{T}_1^s$,using the algorithm used in heating engineering, we calculate the output temperatures $\tilde{T}_2^g, \tilde{T}_2^s$. Then, the constants λ^g, λ^s can be elementarily determined from linear equations (1), (2), using the quantities $\tilde{T}_2^g, \tilde{T}_2^s$:

$$\lambda^g = (\tilde{T}_2^g - \tilde{T}_1^s)/(\tilde{T}_1^g - \tilde{T}_1^s);$$

$$\lambda^s = (\tilde{T}_1^g - \tilde{T}_2^s)/(\tilde{T}_1^g - \tilde{T}_1^s).$$

Conditions (3) ($0 \leq \lambda^g \leq 1, \leq \lambda^s \leq 1$) must be met!

Model Heat Exchanger

Thus, the model heat exchanger is a linear converter. From the definition of parameters λ^g, λ^s, it is obvious that for input temperatures $\tilde{T}_1^g, \tilde{T}_1^s$, the output temperatures of the model heat exchanger exactly correspond to their thermotechnical calculation values. Of course, for other values of input temperatures the model heat exchanger will give some error. However, a numerical study of the magnitude of this error showed that the model heat exchanger (focused on some typical input temperatures) provides a relative error of no more than 10% for a fairly wide range of input temperatures. These calculations were carried out jointly with boiler design specialists, and such satisfactory calculation results were somewhat unexpected.

Model Heat Exchanger

The following more thermophysical interpretation can be given to the introduced model heat exchanger. Let the input temperatures be given $\tilde{T}_1^g, \tilde{T}_1^s$. From thermodynamic considerations it is possible to determine the maximum possible amount of thermal energy transferred to the passive medium (ideal heat exchanger). Let us denote this quantity $Q^*(\tilde{T}_1^g, \tilde{T}_1^s)$. Let $\tilde{Q}(\tilde{T}_1^g, \tilde{T}_1^s)$ be the calculated value of this energy for a real heat exchanger. It is natural to call the quantity $q(\tilde{T}_1^g, \tilde{T}_1^s) = \tilde{Q}(\tilde{T}_1^g, \tilde{T}_1^s)/Q^*(\tilde{T}_1^g, \tilde{T}_1^s) < 1$ as the efficiency coefficient of the heat exchanger. This coefficient depends on the input temperatures $\tilde{T}_1^g, \tilde{T}_1^s$. We ignore this dependence, and for any input temperatures we determine the value of exchange thermal energy by the formula $Q(T_1^g, T_1^s) = q(\tilde{T}_1^g, \tilde{T}_1^s)Q^*(T_1^g, T_1^s)$. Then it turns out (under normally fulfilled conditions) that the model heat exchanger introduced in this way is equivalent to the previously introduced model heat exchanger (1)–(2).

Calculation of the Thermal Scheme

Let the thermal scheme contain m steam path heat exchangers located in some positions of the gas path. The input temperatures of the first position of the gas path and the first heat exchanger of the steam path are given.
It is easy to see that calculating the temperatures of the circuit comes down to solving a system of linear equations $2m \times 2m$, which, for brevity, we will present in the following form:

$$H(k)T = b(k). \tag{4}$$

This system of equations is generated based on equations (1)-(2), taking into account the connection graph of the heat exchanger inputs and outputs.
Let $\tilde{T}^g_{j1}(k), \tilde{T}^s_{j1}(k)$ be the initial approximate values of the input temperatures for heat exchangers j for the iteration k of the algorithm.

Calculation of the Thermal Scheme

0. $k = 1.$

1. Iteration $k.$

We generate model heat exchangers for $\tilde{T}^g_{j1}(k), \tilde{T}^s_{j1}(k)$.

Let $T^g_{j1}(k), T^s_{j1}(k)$ be the values of the input temperatures obtained as a result of the solution (4).

If $|\tilde{T}^g_{j1}(k) - T^g_{j1}(k)| \leq \varepsilon$, $|\tilde{T}^s_{j1}(k) - T^s_{j1}(k)| \leq \varepsilon$, then **STOP.**

$\tilde{T}^g_{j1}(k+1) = \mu\tilde{T}^g_{j1}(k) + (1-\mu)T^g_{j1}(k),$

$\tilde{T}^s_{j1}(k+1) = \mu\tilde{T}^s_{j1}(k) + (1-\mu)T^s_{j1}(k).$

$(\mu \in (0,1)$, for example $\mu = 1/2)$.

$k := k + 1.$

Go to 1.

ε **– accuracy of matching the values of oriented and calculated temperatures.**

Calculation of the Thermal Scheme

The developed thermal calculation method can be considered as a linearization method for solving a system of nonlinear equations. *Pshenichny B.N. : Linearization method. Nauka, M. (1983).* However, the formal use of the method of linearization of system functionals (based on their differentials) does not always lead to success. This is due to the fact that the system of equations for the calculation of output temperatures in heating engineering provides the calculation of output temperatures with acceptable accuracy, but only approximately reflects the physical process of heat transfer. Based on the described algorithm, software has been developed for the problem of calculating rather complex thermal circuits of steam boilers. The application of the algorithm to solving practical problems has shown its fairly high efficiency: to ensure the relative accuracy of the solution ≈ 0.01 it is required ≈ 10 iterations of the algorithm.

Calculation of the Thermal Scheme

We will not provide a formal description of the mathematical model of the optimization problem. In fact, it is traditional: to determine design and control parameters to minimize criteria (cost, weight, etc.) taking into account technological constraints. To use optimization methods, it is necessary to determine algorithms for calculating the gradients of the functionals included in the problem.

Calculation of the Thermal Scheme

Let us consider a brief description of the calculation of temperature gradients of a thermal scheme using the parameter α of some heat exchanger On the abstract level let the vector T^* be a solution to the following system of linear equations:

$$H(\alpha)T^* = b(\alpha), \tag{5}$$

where the matrix H and right-hand sides depend on the scalar parameter α. Differentiating equality (5) with respect to α, we get:

$$H\frac{\partial T^*}{\partial \alpha} = -\frac{\partial H}{\partial \alpha}T^* + \frac{\partial b}{\partial \alpha}. \tag{6}$$

Thus, determining the derivatives of a solution with respect to a parameter α is reduced to solving system (6) with the same matrix as system (5). Of course, this fact is taken into account in the software.

Calculation of the Thermal Scheme

As follows from the above description, the vector of output temperatures T^* in a scheme is the solution to a system of linear equations: $HT^* = b$. Note that the matrix elements H are determined as a result of calculating the thermal scheme (iterative solution of systems of linear equations to coordinate the approximate temperatures $\tilde{T}$ and calculated temperatures T). Thus, the problem of calculating derivatives is reduced to the problem of calculating derivative coefficients λ^g, λ^s for the model heat exchanger with respect to its parameter α. This calculation is carried out using a difference scheme based on thermotechnical calculation of output temperatures.

Software Characteristics

The software of the mathematical model is developed in C++ .
The software input data define information about the following objects:

elements of the thermal scheme (ducts, pipes, heat exchangers);

thermal scheme graph;

functions for calculating physical heat exchangers at given input temperatures;

required solution accuracy.
Software output:

values of all output characteristics of thermal scheme elements;

derivatives of any output characteristic with respect to a given input parameter.

Conclusions

Based on the use of model heat exchangers, an algorithm for calculating thermal schemes of steam boilers and an algorithm for calculating derivatives of heat exchanger output temperatures for various design parameters have been developed. This made it possible to create a fairly effective algorithm for solving specific problems of optimal design of steam boilers. The developed software allows not only to calculate thermal schemes, but also implements algorithms for calculating derivatives of the initial data for all parameters of the thermal scheme. The prototype of the presented software was used to solve real problems in the design of certain types of steam boilers. Complex designs obtained using optimization tools must be refined by design specialists, since mathematical models do not take into account all possible features of real problems.

Literature

1. Zhurbenko, N.G., Laptin, Yu.P.: One method for calculating of thermal schemes. Theory of optimal solution 5, 120–125. V.M.Glushkov Inst. of Cybern. of the NASU, Kyiv (2006) .

2. Shor, N.Z., Zhurbenko, N.G.: A minimization method using space dilation in the direction of the difference of two successive gradients. Cybernetics, 3, 51–59 (1971) .

3. Zhurbenko, N.G., Lykhovyd, O.P.: On numerical efficiency of one modification of the r-algorithm. Computer mathematics, 1, 2–10. V.M.Glushkov Inst. of Cybern. of the NASU, Kyiv (2019) .

4. Levin, M.M., Volkovitskaya, P.I., Laptin, Yu.P., Zhurbenko, N.G.: The use of optimization tools in the computer-aided design system for power boilers CROCUS. Energy and electrification 7, 41–51 (2003) .

5. Aida-zade, K.R., Hashimov, V.A. Optimizing the Arrangement of Lumped Sources and Measurement Points of Plate Heating. Cybern. Syst. Anal., 55, 605–615 (2019).

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Thank you for attention!

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