Improving energy efficiency of industrial grade furnaces with electrical resistance heaters and comparative model-experiment analysis

Borislav Dimitrov[1], Hristofor Tahrilov[2], Angel Marinov[3]

***Abstract* – The current paper suggests a methodology for optimization of insulation for industrial grade furnaces with electric resistance heaters, by coordinated selection of insulating materials. The methodology is based on an objective function for which – minimal losses, mass and size are selected. The results from the simulation procedure are compared against the data from experimental prototype, in order to evaluate the functionality of the model and suggested methodology.**

Keywords – **Energy efficiency ,Mathematical methodology, Optimization, electric heating**

I. Introduction

The process analysis for industrial grade furnaces based on electrical resistance heaters (IGF), done with dedicated models and numerical methods, allows for their optimization, using different objective functions [5]. In order to obtain valid results, the analysis has to be conducted using specified models, with parameters set as close as possible to those of the IGF device.

The aim of the current paper is to suggest a numerical optimization method [1,2,3,4] and apply it with a specialized simulation procedure. In order to be validated the results obtained through the simulation - using a model will be compared against experimental data. The experimental data describes a transient process of preheating the camera of the IGF. The data is obtained from a device with parameters corresponding to those set in the model.

For those specific aims, the mathematical model [1] will be used for optimization of the thermal insulation and the refractory layer of the furnace. The results will be applied to a practical construction that will be tested in order to acquire the experimental dataset.

II. Analysis

The analysis of the set problem can be conducted in the following order:

1. A database of refractory layers and thermal insulations is created. The database is then sorted based on the physical parameters of each representative, more specifically: coefficient of heat transfer, specific heat and weight, price, etc.
2. The geometrical size of the working area of the furnace is determined – this is done when the volume and the shape of the load are taken in account.
3. An initial calculation of the construction is carried out. The initial calculation is used in order to determine the number of required layers of insulation, as well as their width.
4. A model of the furnace is created [2]. The model is evaluated on an iterative basis, using the previously prepared database. The iterations are based on the compatibility of the materials: first layer - refractory, second layer - thermal resistance
5. The analysis of the data allows to select a combination of materials that is closest to the objective function.

The object of the study is the chamber of the IGF, which walls are made of two layers – refractory and thermo resistive. Thus the objective function can be for:

- Minimal weight of the materials for the walls:

$$\begin{aligned} &G = G_1 + G_2 = \\ &= \gamma_1.\delta_1^3 + \gamma_2.\delta_2^3 + 3.\gamma_2.\delta_1.\delta_2.(\delta_1 + \delta_2) + \\ &+ (a_1 + b_1 + c_1).(\gamma_1.\delta_1 + \gamma_2.\delta_2)^2 + \\ &+ (a_1.b_1 + b_1.c_1 + a_1.c_1).(\gamma_1.\delta_1 + \gamma_2.\delta_2) \end{aligned} \quad (1)$$

- Minimal losses for the working time - t_{work}, based of the thermal conductance λ of the materials – $q_{heat}=f(\lambda)$. This can also optionally include the energy accumulated in the walls of the furnace - Q_{ak}, determined by the specific heat C of each layer: $Q_{heat} = \Sigma q_{heat}.\Delta t + Q_{ak}$, where:

$$q_{heat} = \frac{\tau_1 - \tau_{ок.ср.}}{R_\Sigma} \quad (2)$$

$$R_\Sigma = \frac{\delta_1}{\lambda_1.S_{avg1}} + \frac{\delta_2}{\lambda_2.S_{avg2}} + \frac{1}{\alpha_{kl}.S_3} \quad (3)$$

$$\begin{aligned} &Q_{ak} = Q_{ak1} + Q_{ak2} = C_1.\rho_1.\delta_1^3 + C_2.\rho_2.\delta_2^3 + \\ &+ 3.C_2.\rho_2.\delta_1.\delta_2.(\delta_1 + \delta_2) + \\ &+ (a_1 + b_1 + c_1).(C_1.\rho_1.\delta_1 + C_2.\rho_2.\delta_2)^2 + \\ &+ (a_1.b_1 + b_1.c_1 + a_1.c_1).(C_1.\rho_1.\delta_1 + C_2.\rho_2.\delta_2) \end{aligned} \quad (4)$$

[1] eng. Borislav Dimitrov, Ph.D– Technical University of Varna, Bulgaria, assoc professor E-mail – bdimitrov@processmodeling.org
[2] eng. Hristofor Tahrilov, Ph.D – Technical University of Varna, Bulgaria, assoc. professor. E-mail: h.tahrilov@gmail.com
[3] eng. Angel Marinov, – Technical University of Varna, Bulgaria, assistant professor E-mail – igdrazil@abv.bg

Geometrical sizes *a*, *b*, *c*, the width δ_1, δ_2 and their distribution are presented at figure 1.

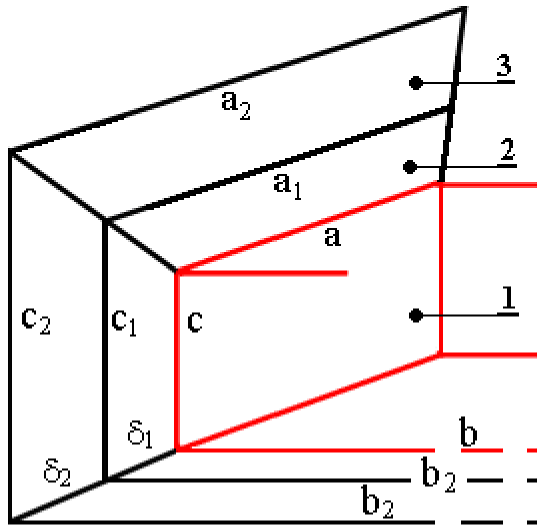

Fig.1. Geometrical sizes a, b, c and widht δ1, δ2 of the walls of IGF: 1 – chamber of the furnace; 2 – refractory layer; 3 – Thermal resistance layer

The optimization procedure is realized using the scan method [5] that allows minimization of the objective function for the given range. [q_{heat}, Q_{ak}]

The limitation conditions are based on the modes of operation that determine different distribution of the two components of the losses.

The database created for the model consists of different materials that are used in the construction of industrial furnaces. The materials are produced and distributed by different companies, thus due to these commercial specifics the materials are cited in table 1 only with their parameters.

The results obtained through the model are presented in graphical and numerical form as follows:

- Table 2 and figure 2 – present the losses dissipated to the surrounding environment when refractory and thermal insulating materials are used. Minimal values are obtained when materials with reduced thermal conduction coefficient are used. The selection of the required combination can be determined based on – weight and price.
- Table 3 and figure 3 – efficiency for one heating cycle: heating and pause during 1 hour.

When the objective function concerns minimal mass with limitation the geometrical size of the furnace, the optimization algorithm remains the same. In this case the database from table 1 is sorted based of the density of the material. The obtained results are as follows:

- Table 4 and figure 4 - present the losses dissipated to the surrounding environment. Based on the data for minimal mass and minimal losses - refractory material number four can be selected from table 5.
- Figure 5 shows the results from a mathematical model (curve 1) and experimental study (curve 2) of the temperature in the transient process of heating. The experimental measurements are made based of a low temperature furnace. The experimental prototype is made of insulation using material number 5 from table 1. Further data for the experimental prototype, its technical parameters as well as additional experimental results are presented in [6].

III. Conclusion

The suggested methodology of optimization of IGF insulation based on mathematical model, allows obtaining notable results. The same method can be used in construction and design of new equipment, as well as in reconstruction for energy efficiency of current equipment.

The difference between results obtained from the model and the experiment, varies between 3% and 7%. Accuracy can be improved by précising the initial parameters set in the model trough series of experiments. This methodology allows simulations to be used in the exploitation of the furnace.

There are practically no limitations to the model as long as the correct objective function is given, and a database for the given elements exists.

The obtained results presented in table and graphical form allow for a continuous correction, limiting the possibility for error.

Acknowledgment

This paper is prepared in the frames of Project MU03/163 “Increasing energy efficiency and optimization for electrotechnological processes and devices”, Ministry of Education Youth and Science, Bulgarian National Science Fund.

References

[1] Димитров Б. “Анализ на изчислителния процес за математичен модел на съпротивителни електропещи”, Списание Електротехника и електроника Е+Е 11-12 2006 страници 78-83.

[2] Димитров Б. “Анализ и моделиране на електротермични процеси и устройства /електросъпротивителни пещи с периодично действие/. Дисертация ТУ-Варна 2009.

[3] Tahrilov H., Dimitrov B., “The analysis of the processes in the electric resistance furnace with the general model”, Tenth international conference on electrical machines, drives and power systems ELMA 2002 page 75-80

[4] Tahrilov H., Dimitrov B. “The general model for researching work of electric resistance furnace”, Tenth international conference on electrical machines, drives and power systems ELMA 2002 page 81-86

[5] Rao Singiresu, “Engineering optimization. Theory and practice” 2009.

[6] http://processmodeling.org

TABLE I

REFRACTORY (1) AND THERMAL INSULATING (2) MATERIALS

Material Number	1		2		3		4		5		6		7		8		9		10	
Type	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Coefficient of thermal conductance λ[W/m.K]	0,6	0,1	0,65	0,15	0,7	0,2	0,75	0,25	0,8	0,3	0,85	0,35	0,9	0,4	0,95	0,45	1	0,5	1,05	0,55
Specific heat C [J/kg.K]	400	300	850	450	500	240	350	190	770	270	650	550	230	660	715	333	908	130	381	381
Density γ[kg/m^3]	1000	300	800	100	1200	200	1350	350	1700	700	950	250	1230	310	1015	115	800	180	2000	420

TABLE II

POWER LOSSES DISSIPATED TO THE ENVIRONMENT (W)WITH MATERIAL COMBINATIONS

		1	2	3	4	5	6	7	8	9	10
		Refractory material									
1	Thermal insulation materials	4796,3	4807,97	4897,66	5009,62	4883,63	5036,72	5295,88	5065,67	5084,91	5091,77
2		6094,05	6139,31	6283,28	6471,96	6352,71	6603,88	6947,43	6702,28	6755,16	6792,92
3		7023,32	7116,97	7317,88	7577,72	7465,37	7795,22	8227,6	7970,64	8063,23	8129,09
4		7733,89	7844,07	8123,58	8437,19	8340,9	8742,2	9252,06	8933,95	9119,14	9216,43
5		8296,32	8435,65	8763,38	9136,23	9050,87	9513,59	10075,5	9764,35	9991,88	10120,2
6		8694,06	8915,72	9252,11	9642,67	9588,05	10080,3	10709,4	10453,1	10638,5	10792,1
7		9064,59	9311,51	9685,07	10111,6	10072,8	10607,6	11284,1	11036,5	11251,6	11430,3
8		9374,83	9648,69	10085,2	10586,9	10536,7	11067	11797,2	11547,9	11788	11988,9
9		9634,94	9933,32	10404,4	10936	10895,5	11456	12217,2	11984,1	12249,3	12471,4
10		9859,26	10178,1	10628,4	11151,6	11150,5	11794,3	12585,1	12364,1	12646	12889,2

TABLE III

EFFICIENCY FOR COMBINATION OF DIFFERENT MATERIALS

		1	2	3	4	5	6	7	8	9	10
		Refractory material									
1	Thermal insulation materials	0,8566	0,8356	0,8296	0,828	0,796	0,8049	0,8309	0,7852	0,7781	0,7697
2		0,8608	0,8384	0,8329	0,832	0,7984	0,8087	0,8379	0,7888	0,7818	0,7733
3		0,8628	0,8399	0,8347	0,8348	0,799	0,8107	0,8411	0,7907	0,7838	0,7753
4		0,8639	0,8407	0,835	0,8360	0,8001	0,8119	0,8428	0,7919	0,7850	0,7765
5		0,8663	0,8425	0,8378	0,8387	0,8013	0,8143	0,8472	0,7943	0,7875	0,7790
6		0,8641	0,841	0,8361	0,8365	0,8005	0,8125	0,8429	0,7926	0,7858	0,7773
7		0,8632	0,8407	0,8355	0,8356	0,8002	0,8119	0,8410	0,7921	0,7852	0,7768
8		0,8703	0,8455	0,8412	0,8430	0,8034	0,8186	0,8543	0,7985	0,7919	0,7834
9		0,8717	0,8466	0,8427	0,8449	0,8042	0,8201	0,8570	0,8000	0,7936	0,7852
10		0,8674	0,8437	0,8390	0,8404	0,8024	0,8163	0,8489	0,7964	0,7897	0,7813

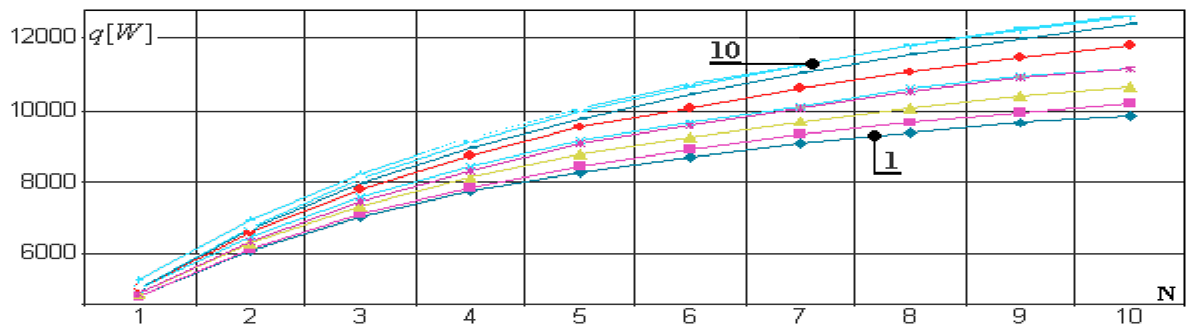

Fig.2. Power losses dissipated to the environment using data from table 2

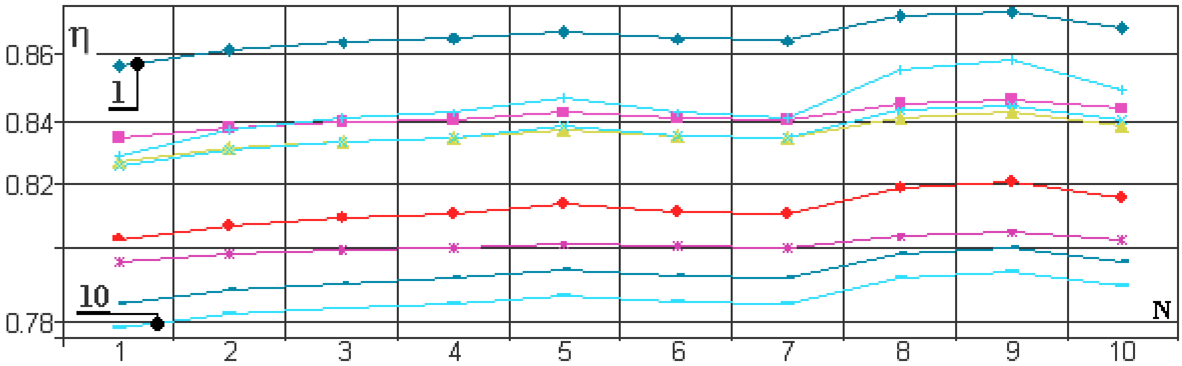

Fig.3. Efficiency using data from table 2

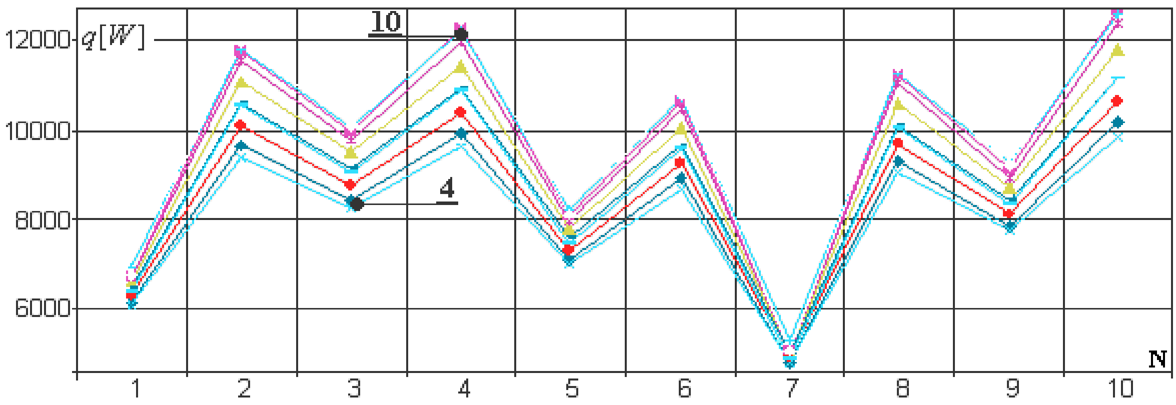

Fig.4. Power losses dissipated to the environment using data from table 4

TABLE IV
POWER LOSSES DISSIPATED TO THE ENVIRONMENT (W)WITH DIFFERENT MATERIAL COMBINATIONS

		1	2	3	4	5	6	7	8	9	10
		Refractory material									
1	Thermal insulation materials	6139,31	6755.16	6603,88	6094,05	6702,28	6283,28	6947,43	6471,96	6352,71	6792,92
2		9648,69	11788	11067	9374,83	11547,9	10085,2	11797,2	10586,9	10536,7	11988,9
3		8435,65	9991,88	9513,59	8296,32	9764,35	8763,38	10075,5	9136,23	9050,87	10120,2
4		9933,32	12249,3	11456	9634,94	11984,1	10404,4	12217,2	10936	10895,5	12471,4
5		7116,97	8063,23	7795,22	7023,32	7970,64	7317,88	8227,6	7577,72	7465,37	8129,09
6		8915,72	10638,5	10080,3	8694,06	10453,1	9252,11	10709,4	9642,67	9588,05	10792,1
7		4807,97	5084,91	5036,72	4796,3	5065,67	4897,66	5295,88	5009,62	4883,63	5091,77
8		9311,51	11251,6	10607,6	9064,59	11036,5	9685,07	11284,1	10111,6	10072,8	11430,3
9		7844,07	9119,14	8742,2	7733,89	8933,95	8123,58	9252,06	8437,19	8340,9	9216,43
10		10178,1	12646	11794,3	9859,26	12364,1	10628,4	12585,1	11151,6	11150,5	12889,2

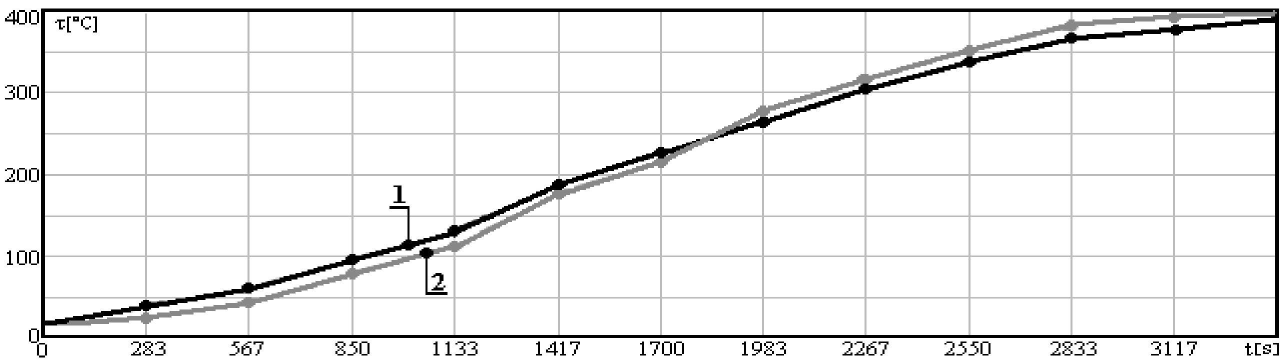

Fig.5. Comparison between experimental (2) and model data(1)