The Modeling of the Heating Resistors in Transient Regime

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Abstract — **The present paper presents an applicative solution of mathematical modeling and simulation for resistive heating elements. A frequently problem, which appears during the use of these ovens, is the rapid aging who leads to the break down of the heating resistors. This model allows the simulation of the transient self-heating regime, as well as of the continuous heating regime. To verify this, the authors have realized a more complex model of an electrical oven with resistors, which integrates the models of the heating resistors as subsystems. The paper presents a part of the simulation results and the conclusions generated by their analysis.**

Index Terms — **circuit simulation, electric heating, electrothermal effects, industrial power systems, system modeling**

I. INTRODUCTION

The ovens with resistors occupy an important place in the industrial electrothermal installations.

This approach is favored by the fact that such an oven can be designed and created not only for different capacities, but also for a wide range of temperatures. As a result of this last aspect, the ovens with resistors can be utilized to melt some materials but also for thermal and thermochemical treatments.

The model proposed for the simulation of the heating elements was necessary for the study of the electrical and thermal processes which appear in such complex industrial installation. The use of the model allowed us to point out more aspects that happen inside the oven during the transient regime, until it reaches the stabilized working regime.

At a superficial approach, the phenomena form inside the oven seems very simple: the resistors supplied from an electrical energy source are getting worm, sending the heat by radiation and convection [1]. The thermal flux reaches the parts to be heated and the walls, which get hot gradually. A part from the energy passes through the walls, to exterior, and is called the lost thermal flux.

In fact, the problems are much more complex. The heating of the electrical resistors is realized with a relatively small time constant, based on a part of the absorbed electrical energy. During this period, the energy emitted as a thermal flux (radiation + convection) depends on the momentary temperature of the resistors, pieces, walls and air, and on the outfit of self-heating from that moment.

On the other side, the temperature of the stratified wall depends on its construction, and grows up based on the thermal flux received from the resistors with a time constant much bigger. The growth of temperature of the different layers from which are made the walls, including the exterior carcass, leads to a continuum modification of the thermal flux lost in the ambient medium. During the heating period of the oven, the part from inside of it gets hot with a proper time constant. Finally, the air from inside the oven takes the heat from the walls but also from the resistors through convection. The value of the thermal flux overtaken by the air and its sense is permanently changing during the heating transient regime of the oven [2].

II. MATHEMATICAL MODELING OF A HEATING ELEMENT

In general, in such an oven, the heating elements are placed on the vault and the hearth of the oven, on the lateral walls, on the backside wall and eventually, on the front side wall (excepting the access door).

The mathematical equations which describe the functionality of the heating resistors are similar in format, but they can differ through the concrete calculus parameters.

In general, for a resistive heating element we can write:

$$i(t) = u(t) / R(T) \tag{1}$$

where: $R(T) = R_0 \cdot C_R(T)$ - the resistance of the resistor depending on its temperature.

If we consider an oven which heats without having other parts in it, then we can write:

$$p_{el} = u(t) \cdot i(t) = \dot{Q}_{store} + \dot{Q}_{rad} + \dot{Q}_{conv} \tag{2}$$

$$\dot{Q}_{store} = d(Q_{store}) / dt = d(m \cdot C_C(T) \cdot \Delta T_w) / dt \tag{3}$$

In the above equations are used the following variables:

m - the mass of the conductor from which it is made the resistor;

$\Delta T_w = T_w - T_0$ - the heating of the resistor;

$C_C(T)$ - the specific heat (in function of the temperature) of the conductor;

T_0 - the initial temperature (considered equal with the temperature of the ambient medium);

$$\dot{Q}_{rad} = \varepsilon \cdot C_n \cdot S_w \cdot \left(T_w^4 - T_1^4\right) = K_1 \cdot \left(T_w^4 - T_1^4\right) \tag{4}$$

where: ε - the blackness degree of the resistor;

C_n - the Stefan-Boltzmann constant;

S_w - the surface of the wire from which the resistor is made;

T_1 - the temperature of the inside surface of the oven's wall;

$$\dot{Q}_{conv} = \alpha \cdot S_w \cdot (T_w - T_a) \qquad (5)$$

where: α - the convection coefficient;

T_a - the temperature of the air within the oven;

In the relations (1)-(5), the values T_a, T_1 and T_w vary during the heating of the oven and, implicitly, the coefficients $C_R(T)$ and $C_C(T)$ depend on the considered moment. But, while the resistor's temperature T_w is being calculated inside the block that simulates the electrical heating resistor, the values T_1 and T_a are input values for this block. They must be calculated dynamically inside other external, interconnected blocks.

III. THE SIMULATION OF THE HEATING ELEMENT

The analysis of the equations (1)-(5) allows us to create the block diagram presented in fig.1.

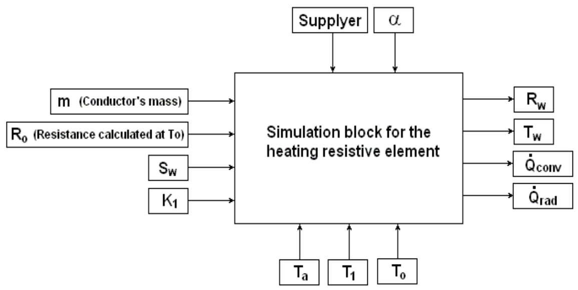

Fig.1 The block diagram of the resistive heating elements

The values m, S_w, α and the resistance calculated at the temperature $T_0(R_0)$ are resulting from the dimensioning calculus of every type of heating resistor. Taking into consideration the fact that inside of an oven, the heating elements can differ depending on the set point (vault, heart, lateral wall, etc.), it is necessary to consider these values as external input values.

To simplify the block which simulates the heating element, the authors preferred to calculate separately the multiplication factor K_1 and to replace it into the input values category (replacing the value ε).

Besides those just said, at the input of the block we attach the values of the effective tension of the power supply and ambient temperature T_0, and the values which are calculated in the exterior of the block: the temperature of the oven's wall T_1 and the one of the air from inside the oven T_a.

From the four output values, only $\dot{Q}_{conv}$ and $\dot{Q}_{rad}$ are values absolutely necessary in the simulation of the oven, and the values R_w (identical with $R(T)$) and T_w (the temperature of the resistor) are used only for the graphic representation of the thermal transient regime from inside the oven.

In fig.2 it is presented the simulation diagram created with the help of Matlab-Simulink kit [3], [5]. The analysis of the scheme emphasizes the fact that the authors have used two functional blocks with polynomial transfer function to represent the variation coefficient of the resistance and of the caloric capacity with the temperature.

The coefficients of the two 3 degree interpolation polynomials have been calculated starting from the data sheets specific for the material chosen to build the heating elements (Kanthal D).

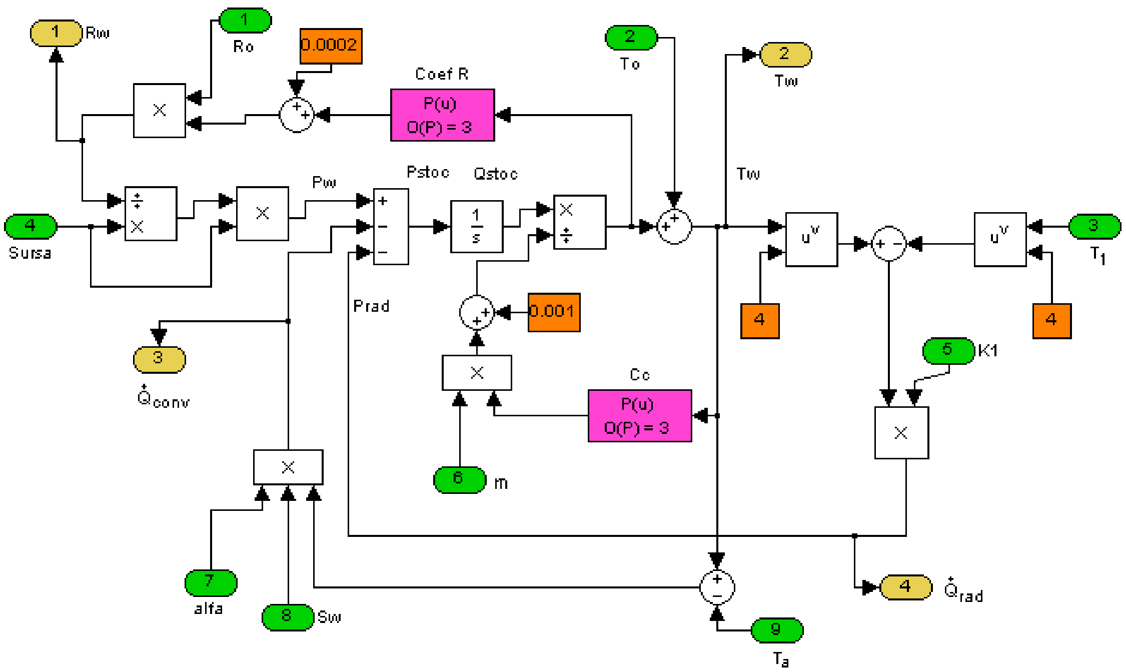

Fig.2 Heating element

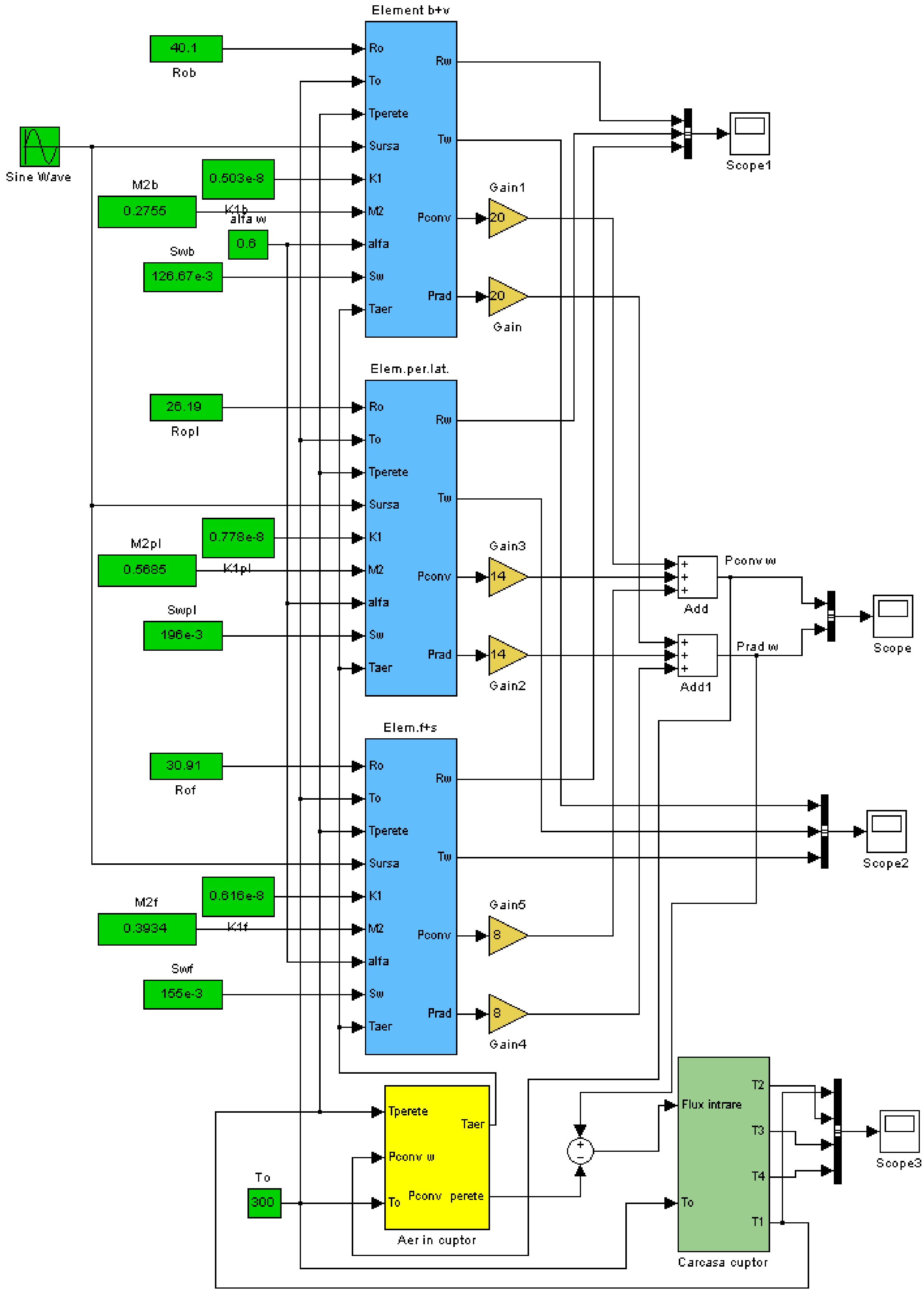

Fig.3 Total diagram of the oven

IV. THE USE OF THE MODEL

The verification and validation of the created model was realized by the authors by using it as a functional block in the general model of the oven (fig.3). When developing the model we have started from the results of a calculus of projecting an oven with an initial power of 150kW.

Taking into account that values as the conductor's mass and the conductor's surface S_w can be different for resistors placed in different zones of the oven, it was necessary that for every type of resistor, to use a bloc that can model and simulate it [4]. At the output, the thermal fluxes yielded by convection and by radiation are pondered with the number of similar resistors and are added, and results the total fluxes of convection and radiation.

$$\dot{Q}_{conv.tot} = \sum_i n_i \cdot \dot{Q}_{conv.i} \tag{6}$$

$$\dot{Q}_{rad.tot} = \sum_i n_i \cdot \dot{Q}_{rad.i} \tag{7}$$

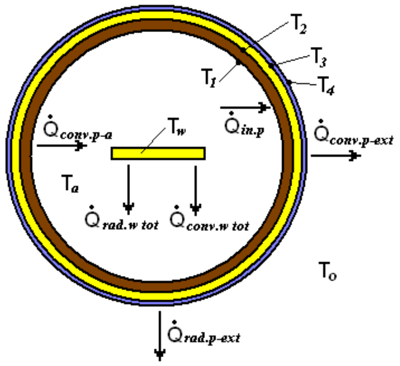

Fig.4 The energetic balance

Taking into consideration the energetic balance of the oven without anything inside (fig.4) we can write for the wall the thermal flux which penetrates the wall:

$$\dot{Q}_{in.p} = \dot{Q}_{rad.w.tot} - \dot{Q}_{conv.w-a} \tag{8}$$

where: $\dot{Q}_{conv.w-a}$ - thermal flux of convection wall-air at the interior of the oven;

$$\dot{Q}_{in.p} = \dot{Q}_{store.w} + \dot{Q}_{conv.w-ext} + \dot{Q}_{rad.w-ext} \tag{9}$$

where: $\dot{Q}_{store.w}$ - thermal flux used for the heating of the wall;

$\dot{Q}_{conv.w-ext}$ - thermal flux of convection yielded by the oven to the ambient medium;

$\dot{Q}_{rad.w-ext}$ - thermal flux of radiation yielded by the oven to the ambient medium;

The diagram from Fig.3 shows the fact that for the simulation of the heating of the air from inside the oven and for the simulation of the thermal transfer through the walls and their heating, there have been created separated blocks using Matlab-Simulink. Within these blocks there have been simulated very carefully the nonlinear variations depending on the temperature of different values, as the specific heat of the air and its convection index.

The block which simulates the walls of the oven is realized of 3 sub-blocks which model the interior refractory layer, the middle thermo insulated layer and the metallic carcass from the exterior. This approach allows the easy modification of the configuration of the wall, let's say for example by adding another layer. This can be simulated very easy, if we add a new block to simulate the intermediary layer. The values T_2 and T_3 represent the temperatures of the intermediary layers, and T_4 represents the temperature at the exterior of the oven's wall (Fig.4).

V. RESULTS

The analysis of the simulations realized based on the projecting calculated data, emphasized that the resistances accumulate energy very quickly, reaching the work temperature in almost 100s (fig.5). During this period, the thermal radiated flux reaches the maximum value; meanwhile the walls are maintaining their temperature at T_0, because of the much bigger time constant.

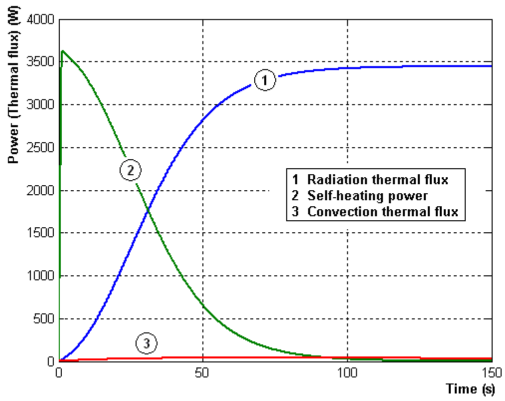

Fig.5 Thermal fluxes of heating elements – high power

In time, the walls get hot and it appears, theoretically, a tendency of reduction of the radiated flux. Practically, the simulations show that this tendency is balanced with the growth of the temperature of heating resistances. If this over-temperature is not controlled, the simulations show that over approximately $2.3 \cdot 10^4$s=6.4h (this time is relatively equal with the one calculated to preheat the oven), the temperature of the resistors overpasses the maximum value for the KANTHAL D material (1600K). The simulations based on the calculated data have been stopped after approximately $3 \cdot 10^4$s, when $T_w > 1800K$ (the melting temperature for KANTHAL D) and practically the resistances would have been damaged. The overheating of the heating resistors and of the wall of the oven (fig.6 and fig.7) appears because of the impossibility to ensure the energetic equilibrium equations for the oven. The modeling and the simulation shows the fact that after reaching an over-temperature admitted for the resistors we must reduce the electrical power transformed in heat by modifying the number of resistors or by supplying with a lower tension.

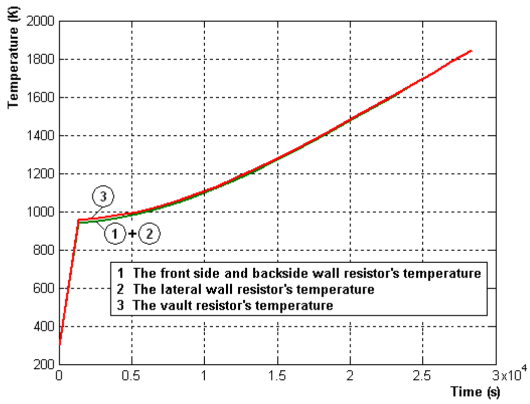

Fig.6 The temperature of the resistors_high power

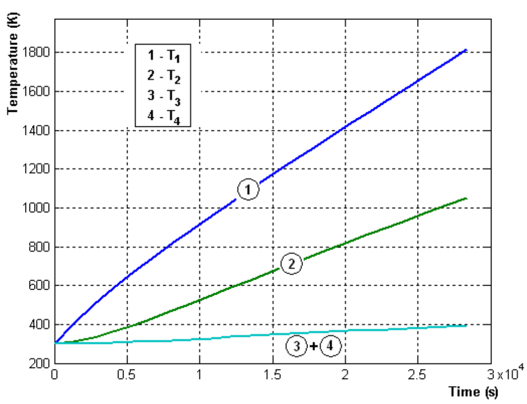

Fig.7 The temperatures of the wall_high power

Another set of simulations, much more conclusive, was realized for the oven equipped with resistors projected so that the power absorbed from the supplier to be equal with 10kW. The results obtained in this case are presented differently for two periods of simulation very different (50s and 15·106s).

In fig.8 and fig.9 are presented the temperatures of the three types of heating elements (placed on the vault and the hearth, on the lateral walls, on the backside and front side wall).

In fig.10 and fig.11 are presented the ways of variation of the total convection and radiation fluxes produced by the heating resistors.

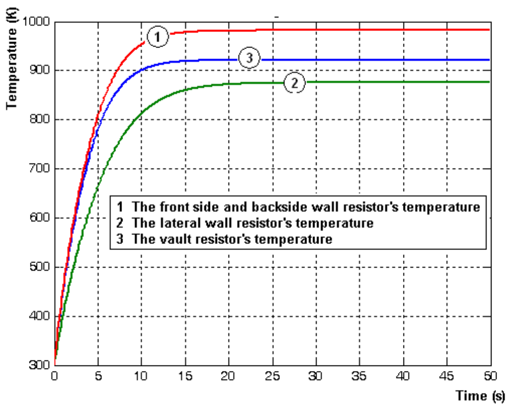

Fig.8 The temperature of the resistors_low power, short time simulation

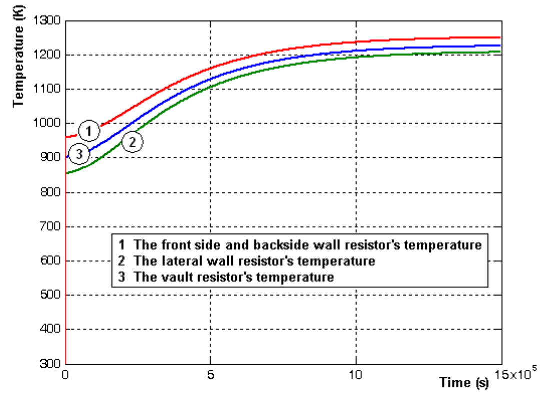

Fig.9 The temperature of the resistors_low power, long time simulation

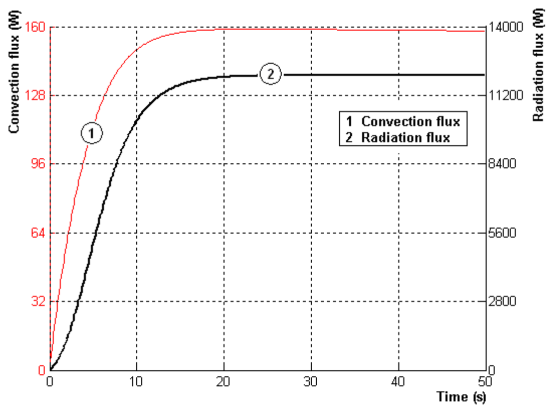

Fig.10 Total thermal fluxes_low power, short time simulation

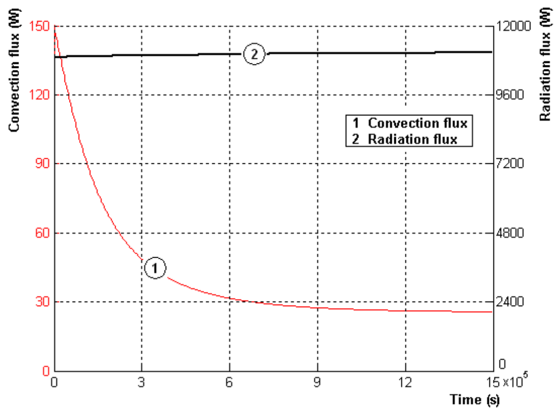

Fig.11 Total thermal fluxes_low power, long time simulation

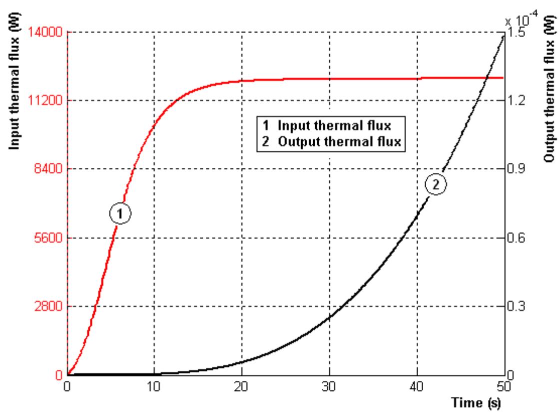

Fig.12 Thermal fluxes through the wall_low power, short time simulation

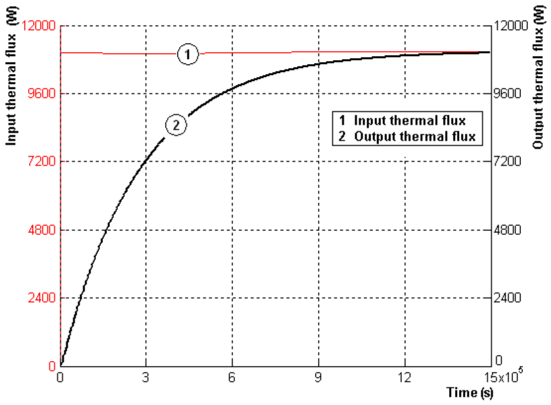

Fig.13 Thermal fluxes through the wall_low power, long time simulation

In fig.12 and fig.13 is exposed the variation way of the thermal flux received by the interior layer of the oven's wall and of the thermal flux yielded by the oven in the exterior.

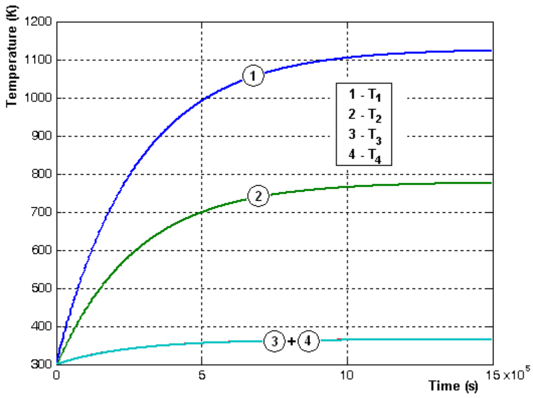

Fig.14 The temperatures of the wall_low power

In fig.14 is represented the temperatures' way of variation at the four separation surfaces of the oven's wall.

VI. CONCLUSIONS

From the paper we can show that at the oven we must control the temperature inside the oven but also the temperature of the resistors. This will allow the automatic control system to maintain the temperature of the resistors within the accepted limits and to avoid their damage. This can be done either by modifying the number of resistances or by supplying with a smaller tension.

The graphics from fig.8 ÷ fig.14 show the fact that we can eliminate the risk of damaging the resistances through overheating by choosing a much smaller resistors power (approximately 15times). On the other side, such a dimensioning correlated with the big value of the time constant of the wall, will lead to a long time for heating (the thermal regime can be considered established only after approximately 12·106s ≈ 3330h). Because such a time period is too long, it is obviously that we need to choose a bigger installed power, which can then be reduced in controlled way, depending on the temperature of the heating elements.

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