An effect of heat insulation parameters on thermal losses of water-cooled roofs for secondary steelmaking electric arc furnaces

E. Mihailov, P. Popgeorgiev, M. Ivanova
University of Chemical Technology and Metallurgy, Sofia, Bulgaria
emil@uctm.edu

ABSTRACT. The aim of this work is research in the insulation parameters effect on the thermal losses of water-cooled roofs for secondary steelmaking electric arc furnaces. An analytical method has been used for the investigation in heat transfer conditions in the working area. The results of the research can be used to choose optimal cooling parameters and select a suitable kind of insulation for water-cooled surfaces.

KEYWORDS. Electric arc furnaces; Heat transfer; Mathematical modeling; Water-cooled roofs.

INTRODUCTION

In order to extend the run time between repairs of electric arc-heated furnaces and to reduce consumption of refractories, in recent years modular water-cooled components are used more frequently in their design. Application of such components, however, involves increased thermal losses, and their faultless operation imposes additional design and operation requirements. It is well-known that, in the presence of water-cooled components, one of the possible ways to reduce thermal losses is application of low-emissivity coatings. Another option is creation of additional heat resistance using refractory insulation. The effect of applying such insulations and coatings depends on the thermophysical characteristics of the materials. Besides, one should expect that, depending on the particular construction, the influence of the thermophysical and radiation insulation characteristics on thermal losses is not simple. That provoked a more detailed study of the water-cooled elements thermal performance under various options of additional measures (application of additional insulation) which would help to establish the influence of various parameters.

MATHEMATICAL MODEL OF HEAT EXCHANGE

The normal work and efficient usage of water cooling elements requires restrictions to be made and a number of special features to be taken in consideration when defining the constructive parameters:

- heat load under the influence of the arcs and metal;
- cooling water movement regime;
- outlet cooling water temperature;
- possibilities for heat losses decrease through protective cooling covering with a definite emissivity and thickness.

From the published models[1-3] for the analysis of heat transfer process in the work area of the electric arc steelmaking furnaces(EASF) using the water cooling elements two ways are used:

1. Outer heat transfer at stationary heat conduction of the wall, roof and metal at which the electric arc can be taken as a point energy source.
2. Outer and inner heat transfer on the basis of immediately heat balance of the whole system.

The heat balance of the working area of EASF can be given with the equation [2]:

$$P_a = Q_m + Q_{c.el} + Q_g + Q_w + Q_{el}, \tag{1}$$

In the heat exchange description, the chamber space of the secondary steelmaking electric arc furnaces (Fig. 1) was reduced to two surfaces ($F_{sum} = F_m + F_{w\text{-}f}$ and $F_{c.el}$) forming a closed space.

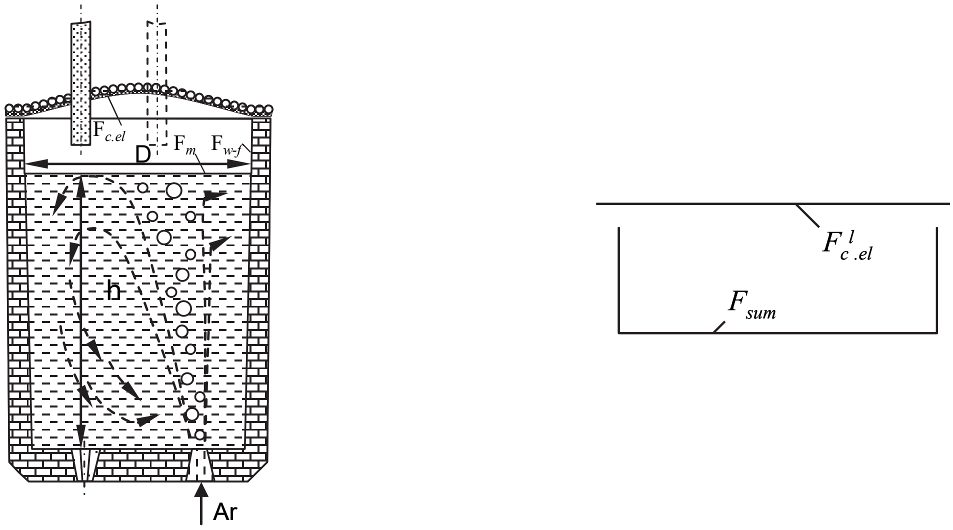

Figure 1: Ladle furnace scheme and heat transfer areas.

Scheme of the heat balance and different heat flows in water-cooled element is presented on Fig. 2.

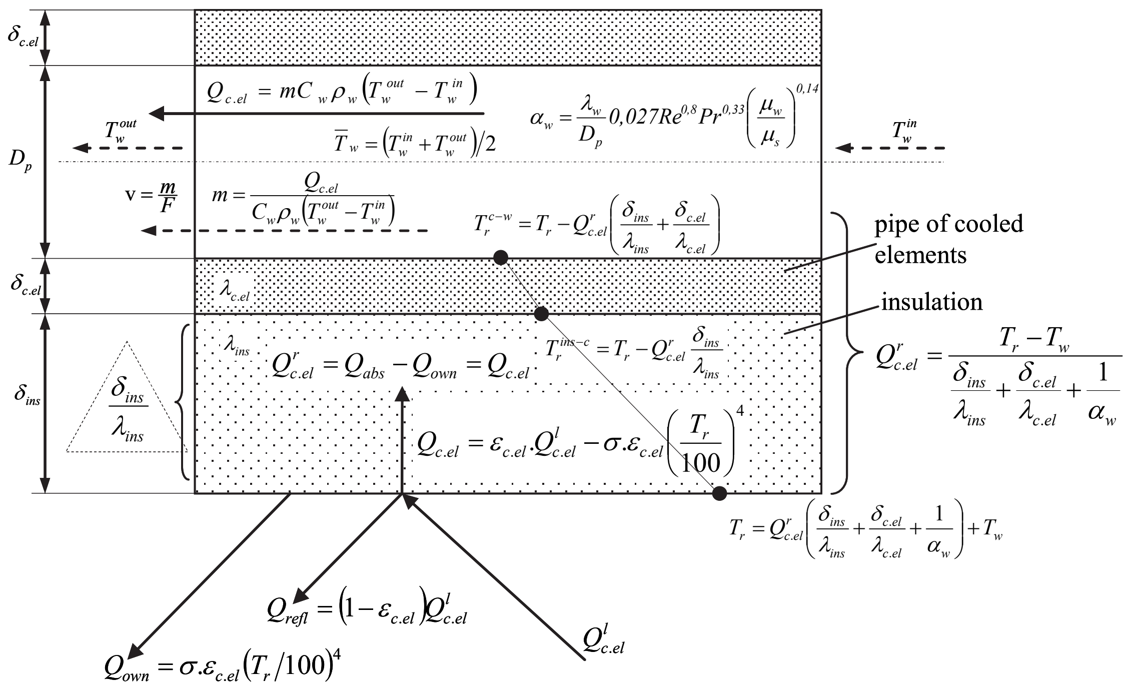

Figure 2: Scheme of the heat balance and different heat flows in water-cooled.

In the mathematical model is accepted, that the heat removed by cooling water ($Q_{c.el}$) and resultant heat flux are equal:

$$Q_{c.el} = Q^{r}_{c.el} \tag{2}$$

For the heat losses by the roof can be taken very well know equation:

$$Q^{r}_{c.el} = \frac{T_r - T_w}{R + \dfrac{1}{\alpha_w}} F_{c.el} \tag{3}$$

The heat float falling through the flat cooling element can be determined by the following equation [2]:

$$Q^{l}_{c.el} = k_s \left[k_r + (1 - k_r \varepsilon_{c.el})(1 - \varepsilon_{ef}) \frac{F_{c.el}}{F_{sum}} \right] P_a + (1 - k_g) C \left[\left(\frac{T_{rad}}{100} \right)^4 - \left(\frac{T_r}{100} \right)^4 \right] F_{c.el} \tag{4}$$

Determining of the heat lose according Eq. (3) T_r and α_w are unknown. The coefficient α_w can be defined from the equation [4]:

$$Nu = \frac{\alpha_w D_p}{\lambda_w} = 0{,}027 Re^{0{,}8} Pr^{0{,}33} \left(\frac{\mu_w}{\mu_s} \right)^{0{,}14}$$

For the purposes of the study, a mathematical model of the external heat exchange, under steady state thermal condition of walls and metal where the electric arc is viewed as energy point-source, was made. For computer implementation of the mathematical model an algorithm (illustrated by a simplified block diagram on Fig. 3) was developed. The object of the study was the construction of real 100t secondary steelmaking electric arc installation.

AN EFFECT OF HEAT INSULATION PARAMETERS ON THERMAL LOSSES OF WATER-COOLED ROOFS

Thermal losses through cooling water have been calculated for various insulation thicknesses and types of materials. The thermophysical characteristics of silica, magnesite, chromitee, shamote, magnesite-chromite and chromite-magnesite refractory of various thicknesses and their own emissivity have been used as input data for the study. For faultless operation of the water-cooled roof panel, water temperature at the outlet shall not exceed 60°C. It was assumed that water temperature at the panel outlet was 30°C, and water temperature difference between the panel inlet and outlet was ΔT=10 °C.

As a result of the calculations, the thermal losses, the average heat transfer coefficient to the water, and the required water flow rate ensuring compliance with the restrictions imposed on outlet water temperature were obtained.

The resulting heat losses and temperature changes on the insulation surface depending on its thickness for silica, magnesite, chromitee, shamote, magnesite-chromite and chromite-magnesite are presented in Fig. 4 to 9. The thermophysical characteristics of these materials are presented on Tab. 1.

From Fig. 4 it can be seen that, in the case of silica insulation depending on the insulation thickness 1mm to 20 mm, the thermal losses decrease with 50% from 1.83MW to 0.92 MW, or 8.3 % from the heat generated from the electric arcs. At the same time surface thermal resistance increases up to 0.01 m^{2}K/W and temperature - to 950°C.

Similar values can be seen in the case of cromite insulation (Fig. 5) where the surface temperature increases up to 820 °C and temperature resistance- up to 0.013 m^{2}K/W.

The magnesite insulation (Fig. 6) ensures heat losses in the range of 13% to 12.8% from the heat generated from the electric arcs, i.e. thermal losses decrease with very low values of 0.2%. This is in consequence of the high thermal conductivity with values of thermal resistance 0.003 m^{2}K/W. The surface temperature increases up to 300 °C.

The shamote insulation (Fig. 7) has a high level of thermal resistance, which at thickness of 0.012m is 0.012 m²K/W, the surface temperature increases up to 1040°C and heat losses decrease from 1.76MW to 0.73MW by 60%.

Kind of insulation	Emissivity ε	Coefficient of conductivity λ, W/m.K
Silica	0.70	1.58+0.00038.T
Magnesite	0.38	6.28-0.00270.T
Shamote	0.60	0.88+0.00023.T
Chromite	0.85	1.28+0.00410.T
Magnesite-chromite	0.82	4.10-0.00160.T
Chromite-magnesite	0.93	2.80-0.00087.T

Table 1: Thermophysical characteristics of insulating material.[5]

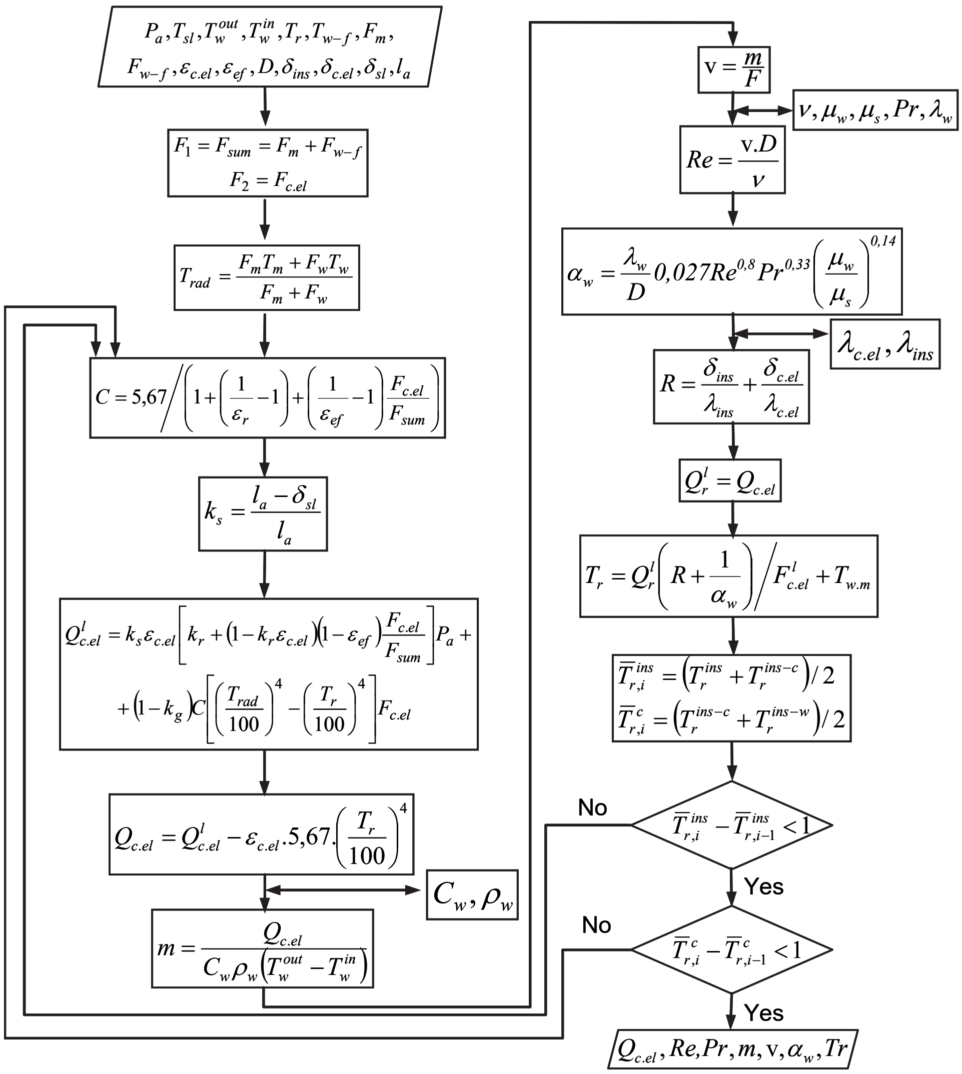

Figure 3: Simplified block diagram of the numerical algorithm.

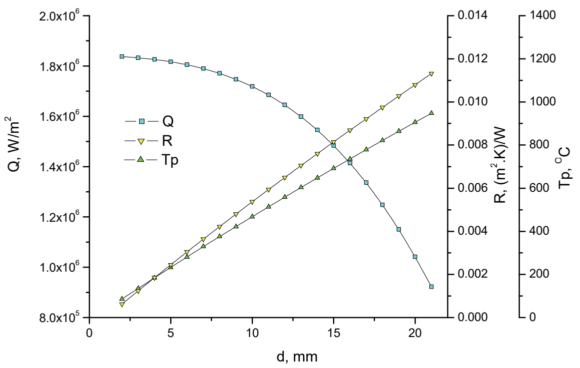

Figure 4: Heat losses, surfaces temperature and thermal resistance of insulation as a function of silica insulation thickness

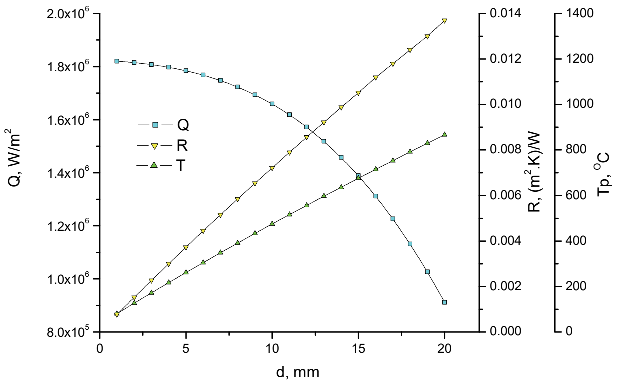

Figure 5: Heat losses, surfaces temperature and thermal resistance of insulation as a function of chromite insulation thickness.

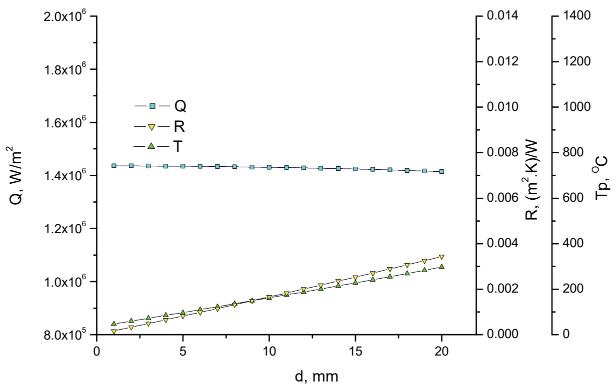

Figure 6: Heat losses, surfaces temperature and thermal resistance of insulation as a function of magnesite insulation thickness

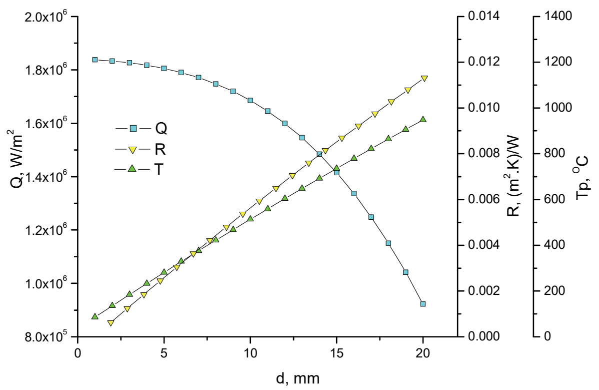

Figure 7: Heat losses, surfaces temperature and thermal resistance of insulation as a function of shamote insulation thickness

In the case of chrome-magnesite (Fig. 8) insulation the heat losses decrease to 14 % and the surface temperature is 580°C for 0.020m thickness of insulation.

For magnesite-chromite insulation (Fig. 9) these values are 15%, thermal resistance R=0.005 and surface temperature Tr= 420°C

Fig.10 shows that, in the case of shamote insulation, thermal losses are smaller, which can be explained by the lower heat conductivity of this type refractory. At the same time, with such insulation, surface temperatures are higher than those of the rest insulations.

It can be seen that all insulations have a higher level of initial values of heat losses than magnesite and with increasing of insulation thickness their heat losses decrease. It can be explained with the lower value of emissivity (ε=0.38) of magnesite material than the emissivity of the other materials.

With the increase of magnesite insulation thickness to 0.008 m, the surface temperature increases up to 136°C and the heat losses are the same as in the case of shamote, but the surface temperature of shamote insulation increases up to 730°C. At about 0.015m thickness of the magnesite insulation, the heat losses are similar to the heat losses of magnesite-chromite and crome-magnesite, but the surface temperatures of the cooling element for the last two materials are respectively 319°C and 436°C.

A graphical summarizing of investigated materials behavior is presented on Fig. 10.

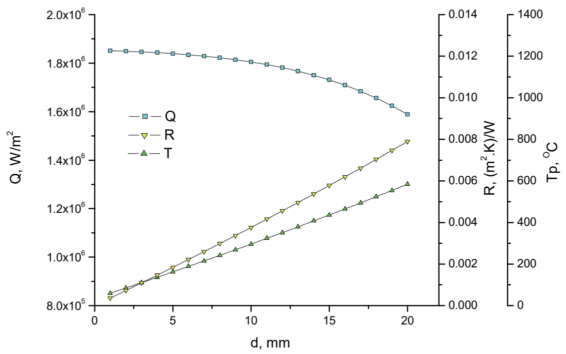

Figure 8: Heat losses, surfaces temperature and thermal resistance of insulation as a function of chrome-magnesite insulation thickness

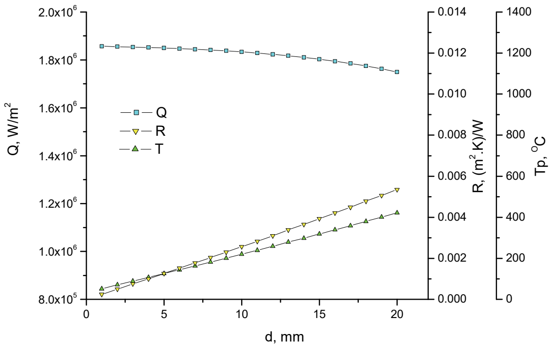

Figure 9: Heat losses, surfaces temperature and thermal resistance of insulation as a function of magnesite-chromite insulation thickness

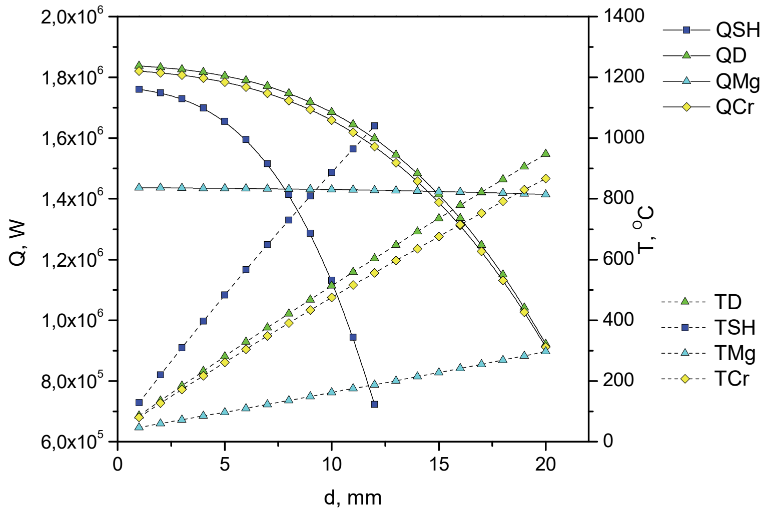

Figure 10: Heat losses and surfaces temperature of insulations as a function of insulation thickness.

As seen from the obtained results and the thermal balance of the water-cooled element (Fig. 2), with the same insulation thickness and lower thermal conductivity coefficient, the surface temperature is higher compared to that in the case of higher thermal conduction, whereupon the own radiation heat flux (Q_{own}) of the roof cooling element is higher. In the case of lower insulation thickness, the surface temperatures are lower, and under such conditions and lower emissivity (ε<0,5), the reflected heat flux from the surface (Q_{refl}) has a higher value than the absorbed flux (Q_{abs}) and the own radiation of the surface is lower. For larger thickness and lower values of thermal conductivity, the surface temperature becomes higher than 500°C, and the own radiation of roof cooling element has a higher effect on the surface's thermal balance. Under such conditions, the cooling element participates in the heat transfer with significant quantities of the radiation heat flux from own radiation, depending, to the highest extent, on the surface temperature and surface emissivity and has the behaviour of a refractory-brick roof with all their shortcomings.

For the same insulation thickness and higher thermal conductivity coefficient, the surface temperature is lower compared to that in the case of low thermal conductivity, consequently the own radiation (Q_{own}) of the water-cooling element is lower and under such conditions and lower emissivity (ε<0.5), the reflected heat flux from the surface (Q_{refl}) has a higher values than the absorbed flux (Q_{abs}).

Obviously, the use of such heat insulating materials for heat losses reduction is restricted by insulation thickness, levels of thermal conductivity coefficient and emissivity.

The high level of the surface temperature has to be avoided, because the higher surface temperatures are sources of thermal gradients and thermal stresses and can lead to destruction of insulations.

Therefore, the application of insulation materials on water-cooled roofs should be limited in their safety working conditions, i.e. in the range of surfaces temperatures with low values of thermal gradients and thermal stresses across insulation thickness.
As can be seen from Fig.10, magnesite can be recommended as an appropriate material with its own low values of emissivity, surface temperature of insulation and thermal gradient across insulation thickness.

4.CONCLUSIONS

A detailed investigation of the water-cooled elements thermal performance under various options of application of additional insulation has been carried out.
An analytical study was made to find the possible ways of reducing the thermal losses in the water-cooled roof of a 100t secondary steelmaking electric arc furnace.
As a result of the study it was found that, magnesite can be recommended as an appropriate material with its own low values of emissivity, thermal losses and surface temperature of insulation during the work.

REFERENCES

[1] Velchev, A., Mihailov, E., Petkov,V., Investigation of the parameters influence over the heat work of the water-cooling roofs for small electric arc furnace, International Conference "The Efficient Use of Energy in Metallurgy", Varna, Bulgaria, 94 (1999) 100-105.
[2] Lingorsky, N., Heat transfer in electric arc furnaces equipped with water cooled panels, Iron and Steel Engineer, 10 41(1988).
[3] Toulouevski, Y., Zinurov, Il., Innovation in Electric Arc Furnaces: Scientific Basis for Selection, Springer-Verlag GmbH, (2013) 215-237
[4] Kreit, F., Black, W, Basic Heat Transfer, Harper and Row, Publishers, New York, (1980).
[5] Mastrukov, B., Theory, Constructions and Calculations of metallurgical Furnaces, Moscow, Metallurgy, (1986) (in Russian).

APPENDIX

List of symbols:
C - coefficient of heat transfer through radiation W/m^{2}K^4;
C_w - specific heat capacity of water, kJ/m^{3}K;
D_p – diameter of cooling panel pipe, m;
$F^l_{c.el}$, $F^r_{c.el}$, F_m, F_{w-f} -heat absorbing area of insulation, cooling element, metal and wall, m^2;
i – consecutive number of iteration;
k_g - coefficient /≈0,1/;
k_r - coefficient, marked the direct absorbing of the cooling element surface from the arc;
k_s - arc screening coefficient;
l_a - length of arc, m;
m - volumetric flow of cooling water, m^3/s;
P_a - heat generated by arcs, W;
Pr , Re - Prandtl and Reynolds numbers;
Q_{w-f} , $Q_{c.el,}$ - heat removed by walls and cooling water, W;
$Q^l_{c.el}$, $Q^r_{c.el}$ - radiant heat flux fall on the roof and resultant heat flux, W;
Q_{own} , Q_{refl}, Q_{abs} – own, reflected and absorbed radiant heat flux by roof, W;
Q_m - heat observe by metal,W;
$Q_{c.el}$ - heat removed by cooling water,W;
Q_g-heat outlet by gases,W;
Q_w - heat removed by walls,W;

Q_{el} - heat removed by electrodes, W.
R - heat resistance, m^2K/W;
T_r - surface temperature of the roof, K;
$\overline{T}_r^{ins}$, $\overline{T}_r^{c}$ - average temperature of insulation and wall of cooling panel, K;
$T_r^{ins\text{-}c}$ - temperature between insulation and cooling panel , K;
$T_r^{c\text{-}w}$ - temperature between cooling panel and water , K;
T_{rad} - radiation temperature of the total surface $F_{sum}=F_{w\text{-}f}+F_m$, K;
T_m, T_w - temperature of the metal and wall, K;
T_w^{in}, T_w^{out} - inlet and outlet temperature of the water, K;
T_w – average temperature of the cooling water, K;
v – cooling water velocities, m/s;
α_w - heat transfer coefficient by the water, W/m^2K;
$\delta_{c.el}$, δ_{ins}, δ_s - thickness of cooling elements, insulation and slag layer, m;
$\lambda_{c.el}$, λ_{ins}- coefficient of thermal conductivity of cooling elements and insulation, W/mK;
$\varepsilon_{c.el}$, ε_{ef} - emissivity of heat roof absorbing surface and effective emissivity of F_{sum};
μ_s - dynamic viscosity of the water at the temperature of the surface, $N.s/m^2$;
μ_w - dynamic viscosity at average temperature of the water, Ns/m^2;
ρ_w - density of the water, kg/m^3;
ν - kinematic viscosity at average temperature of the water, m^2/s.