Simulation and optimization of high power super heater reflectors usable in electrical furnaces for heat loss reduction

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Abstract

Super heater elements concentrated in very high and clean power at temperature up to 1800 ºc is needed for aluminium melting, oil drying equipment using for power transformers and same that material. There fore, always it is need to minimize power consumption and increase effectiveness at power reflector customers. This means to minimize heat losses in the High Power Reflector, and to optimize heat performance with respect to output power and temperature distribution. This can be done by altering the size and form of the insulating ceramic fiber to have as much power as possible 'reflected' out from the module. It can also be done by altering the size and form of the element .It has been done and the task solved mainly by heat transfer simulations, using COMSOL and MTLAB software's. To minimize the number of different designs (and thus the number of calculations) were studied; it is also done that statistical methods for experimental design used to determine which designs should be used in the calculations. When an optimal solution has been found, it has been tested at factory's facilities, with two reference designs.

Keywords: reflector, simulation, element.

1. Introduction

Molybdenum disilicide (MoSi2) are resistance type heating elements made of a dense ceramic-metallic material which can produce furnace temperatures approaching 1800°C. Although more expensive than traditional metallic elements, MoSi2 elements are known for their longevity due in part to a protective quartz layer that forms on the surface of the element "hot zone" during operation.

The MoSi2 elements are made to industry standard established resistance values, dimensions and geometries, and therefore are interchangeable with other manufacturers of molybdenum disilicide elements.

The $MoSi_2$ elements are graded in many maximum temperature ranges, same 1700°C (3090°F) and 1850°C (3270°F). Elements are available in many shapes and forms (see examples shown below).

Benefits of $MoSi_2$ elements include high temperature operation (in air), long element life and the ability in some cases to replace any failed elements hot.

Customers of The MoSi2 elements enjoy two key added benefits – first, unparalleled price and second, experienced engineering support. Anyone can sell MoSi2, but knowing how to design the system is where MoSi2 excels. MoSi2 systems must be engineered for customer to get the best performance and optimum service life. The engineers can assist in:

analyzing the relationship between the furnace temperature, element temperature and the element surface load selecting the element surface load according to the furnace construction, atmosphere and operating temperature choosing the most suitable element size and style for customer application designing a new furnace with MoSi2 or converting from gas or oil fired to a MoSi2 based electric heating system determining if one of MoSi2 Power Pack systems can work for application.

MoSi2 heating element is used in the high temperature under oxidizing atmosphere. It will form the SiO2 film which can keep the element from being melted. During the oxidizing process, the SiO2 protecting film is formed again when the element continues to be used. The MoSi2 heating element must not be used in the temperature between 400ºC and 700ºC for a long time; otherwise the element will be cremated under the strong oxidizing function in the low temperature.

The resistance of MoSi2 heating element increases fast along with the temperature going up. This means that when the elements are connected to a constant voltage, the power will be higher at lower temperatures and will be graduadlly reduce with increasing temperature, thus shortening the time for the furnace to reach operating temperature. Furthermore, as the power of the elements decreases, the danger of overheating will be reduced. Under the normal condition, the elements resistance does not change along with used time generally. So the old and the new element can be used together. Element length, diameter and distance between elements- element with reflector wall and bottom; depth and dimensions of reflector, reflector material (material of surface, insulation and back of reflector), and design of reflector, power and sealed system are important in temperature distribution and so losses. Low losses and have high temperature efficiency in 20 centimeter in top of element is the aim of this optimization.

2. Problem definition

It's necessary to create optimum heating solutions for each power reflectors.

One of manufacturer same as RATH and KANTHAL many heating solutions is called Superthal, which consist of vacuum formed ceramic fiber shapes with an integrated Kanthal Super ceramic ($MoSi_2$) heating element. The Super ceramic heating elements can be operated at element temperatures up to 1850°C.

The Superthal High Power Reflector is a compact fiber insulated modular heater with so-called 'cubic' Kanthal Super elements, see Fig. 1. It is designed for a power of up to 110kW/m^2 at 1650°C.

Multiple units can easily be joint together in different configurations e.g. in rows or squares. The Superthal High Power Reflectors are used wherever a concentrated high power at temperatures of up to 1650°C is needed, for instance in single billet heating, aluminum melting furnaces or ladle heaters.

Figure 1. A Kanthal Superthal High Power Reflector

A reflector dimension that has been used for simulation is: 600×600mm in wide and so 230mm in depth, voltage and current are 66v and 605 Amp. at 1650 ºC respectively; power density is 110 w/m^2 and finally element type is 12/24mm.

2.1 Description of task

There is always a need to minimize power consumption and increase effectiveness at customers. In this case it means to minimize heat losses in the Power Reflector, and to optimize heat performance with respect to output power and temperature distribution. This can be done by altering the size and form of the insulating ceramic fiber to have as much power as possible 'reflected' out from the module. It can also be done by altering the size and form of the element.

It is suggested that the task is solved mainly by heat transfer simulations, using e.g. some FEM software and so COMSOL and MTLAB software's.

To minimize the number of different designs (and thus the number of calculations) that need to be studied, it is also suggested that statistical methods for experimental design are used to determine which designs should be used in the calculations.

When an optimal solution is reached, this will be tested at Kanthal's facilities, together with one or two reference designs.

3. Material properties

Thermal conductivity (W/m K), heat capacity (J/kg K) and resistivity (Ωm) are shown in figures 2,3 and 4 and so in this element emissivity is $\varepsilon = 0.7$

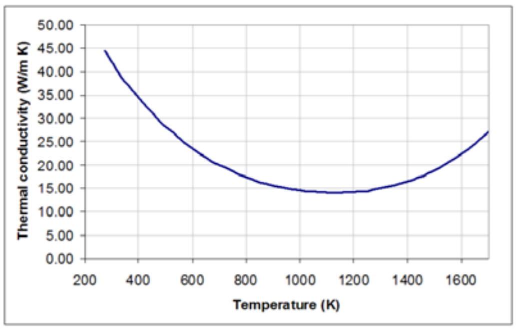

Figure 2. Thermal conductivity (W/m K)versus temperature

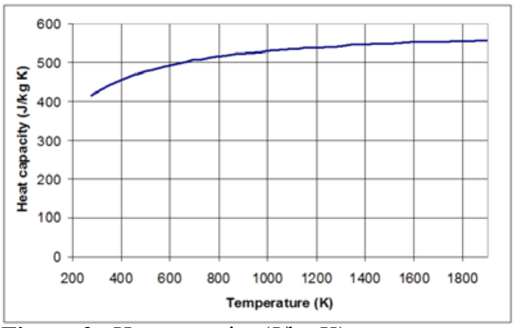

Figure 3. Heat capacity (J/kg K) versus temperature

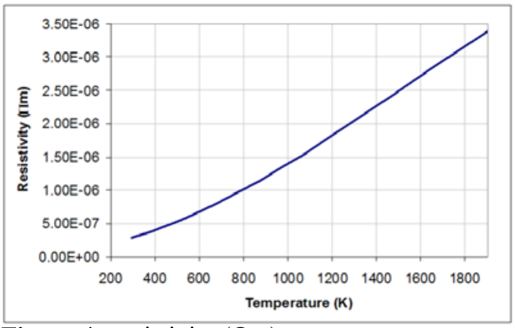

Figure 4. resistivity (Ωm) versus temperature

Table 1. Element for 12mm hot zone diameter and fiber panel characterizes

Element	**Min**	**Max**	
Number of shanks	4	25	4, 6, 12, 16, **20**, 25
Hot zone length, Le (mm)	100	300	
Terminal length, Lu (mm)			150 mm for 12 mm hot zone.
Center-to-center distance, a (mm)	35/45	60/80	Depends on the diameter of the hot zone (9 or 12 mm).
Hot zone diameter, d (mm)	9	12	12mm
Terminal diameter, c (mm)	18	24	For 12 mm hot zone, the terminal is 24 mm.
Surface load (W/cm^2)	10	40	
Current (A)	200	700	605
Plug and Fiber panel			
Material quality	1400	1700	1700
Size			600*600*230mm
Shape			To be determined by sim.
Heat transfer coefficient			100w/m^{2}k^4
Emissivity			0.7
Coefficient of radiation			5.67w/m^2°C

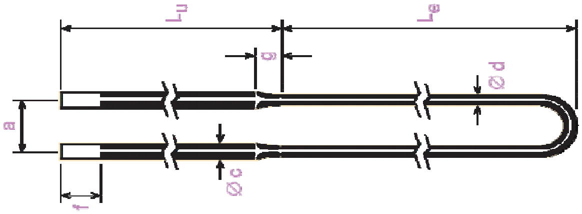

Figure 5. Element

3.1 1600°C VACUUM FORMED CERAMIC FIBER PRODUCTS

Vacuum formed reflector exhibit excellent thermal conductivity, good compressive strength and exceptional thermal stability. This combination of physical properties allows reflector products to be used in hot face applications at temperatures up to 1500°C (2732°F) as well as efficient back-up insulation. By surface-rigidizing, heating elements are able to be effectively mounted on the board or shape.

Table 2. Technical data of reflectors

Classification/Service Temperature

1600°C/1500°C 2912°F/2732°F

Chemical Composition

65% Al2O3 34% SiO2

Density 300 kg/m3 18.6 lb/ft3

LOI (@1000°C, 6h)

KVS 161 4% KVS 164 0%

Linear Thermal Shrinkage (KVS 161) 24 hours:

@ 1300°C (2372°F) - 0.5%

@ 1400°C (2552°F) -1.0%

@ 1500°C (2722°F) -1.5%

[“-“ = shrinkage “+” = expansion]

Compressive Strength 0.15 MPa

(@ 10 % compression) 21.9 lb/in2

Cold Bending Strength (MOR) 1 Mpa

(3 Point Bend) 146 lb/in2

Specific Heat 0.92 J/g·°C 0.22 BTU/lb·°F

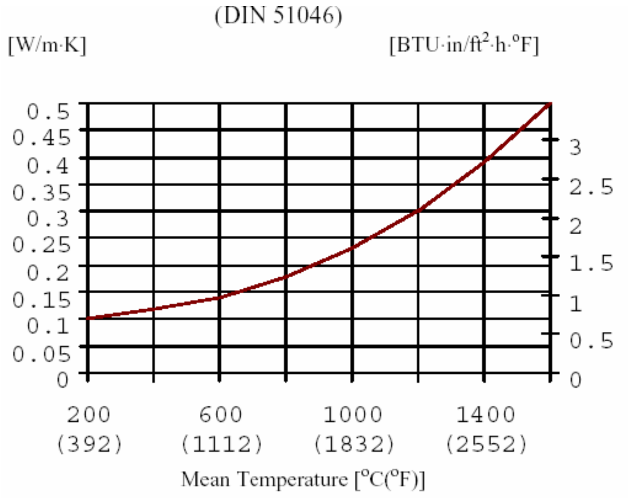

Figure 6. Thermal conductivity of ceramic reflectors

4. The Heat Equation

The mathematical model for heat transfer by conduction is the heat equation:

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (-K\nabla T) = Q$$

Quickly review the variables and quantities in this equation:

T is the temperature.

ρ is the density.

C is the heat capacity.

C_p is the heat capacity at a constant pressure.

C_v is the heat capacity for a constant volume.

k is the thermal conductivity.

Q is a heat source or heat sink.

For a steady-state model, temperature does not change with time and the first term containing ρ and C vanishes. If the thermal conductivity is anisotropic, k becomes the thermal conductivity tensor k:

$$k = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix}$$

To model heat conduction and convection through a fluid, the heat equation also includes a convective term. this formulation in the General Heat Transfer application mode as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-K\nabla T + \rho C_p T u) = Q \qquad (1)$$

Where u is the velocity field, this field can either be provided as a mathematical expression of the independent variables or calculated by a coupling to a momentum balance application mode such as Incompressible Navier-Stokes or Non-Isothermal Flow.

The heat flux vector is defined by the expression within the parentheses in the equation above. For transport through conduction and convection this equation yields:

$$q = -K\nabla T + \rho C_p T u$$

Where: q is the heat flux vector. If the heat transfer is by conduction only, q is determined by: $q = -K\nabla T$

Heat capacity refers to the quantity that represents the amount of heat required to change one unit of mass of a substance by one degree. It has units of energy per mass per degree. This quantity is also called specific heat or specific heat capacity.

4.1- Boundary Conditions

We use two different types of boundary conditions, the Dirichlet type and the Neumann type. The Dirichlet type boundary condition is used to set a temperature on the boundary:

$$T = T_0$$

While the Neumann type condition is used to set the heat flux on the boundary:

$$-n \cdot q = q_0 \qquad (2)$$

Where:

q is the heat flux vector.

n is the normal vector of the boundary.

q_0 is inward heat flux, normal to the boundary.

The Heat Transfer Module uses the following, more general and formulation of Equation 2 :

$$-n \cdot q = q_0 + h(T_{\inf} - T) \qquad (3)$$

This formulation allows you to specify the heat flux in terms of an explicit heat flux q_0 and a heat transfer coefficient, h, relative to a reference temperature, $T_{\inf}$.

The thermal insulation condition is obtained by setting $q_0 = 0$. This is also the case for symmetry boundaries.

For heat transfer problems involving radiation, additional terms are added on the right side of Equation 3 to represent the radiative heat flux. This is covered in the next section.

4.2- Radiative Heat Transfer

So far we have considered heat transfer by means of conduction and convection. The third mechanism for heat transfer is radiation. Thermal radiation denotes the stream of electromagnetic waves emitted by a body that has a certain temperature. Here we will study the theory behind the radiative heat transfer process that occurs on the surface of a body.

The radiosity is the sum of the reflected radiation and the emitted radiation:

$$J = \rho G + \varepsilon \sigma T^4 \qquad (4)$$

The net radiative heat flux into the body is obtained by computing the difference between the irradiation and the radiosity:

$$q = G - J \qquad (5)$$

Using Equation 4 and Equation 5 , we eliminate J and obtain the following expression for the net inward heat flux into the body:

$$q = (1-\gamma)G - \varepsilon \sigma T^4 \qquad (6)$$

Besides the assumption that the surface is opaque, we also assume that the surface is diffusive-gray. For diffusive-gray surfaces, we can assume the following for the reflectivity and the emissivity:

$$\alpha = 1 - \gamma = \varepsilon \qquad (7)$$

By inserting Equation 7 into Equation 6 we eliminate the reflectivity from Equation 6 and express the net radiative heat flux q in the inward direction as:

$$q = \varepsilon (G - \sigma T^4) \qquad (8)$$

The expression above denotes the net radiative heat flux into a boundary.

We distinguish between two different types of radiative heat transfer: surface-to-ambient radiation and surface-to-surface radiation. Equation 8 holds for both radiation types. However, the irradiation term, G, is different for surface-to-ambient and surface-to-surface radiation. The irradiation term and the resulting radiative heat flux for both radiation types are derived in the sections below.

4.3- SURFACE-TO-AMBIENT RADIATION

For surface-to-ambient radiation, assume the following:

The ambient surroundings in view of the surface have a constant temperature Tamb.

The ambient surroundings have the properties of a black body, that is, emissivity and absorptivity equal to 1 and reflectivity equal to zero.

These assumptions allow us to explicitly express the irradiation on the surface as:

$$G = \sigma T_{amb}^4 \qquad (9)$$

By inserting Equation 9 into Equation 8 we obtain the net inward heat flux for surface-to-ambient radiation:

$$q = \varepsilon \sigma (T_{amb}^4 - T^4) \qquad (10)$$

4.6- Electromagnetic equations:

To derive the equation system this mode solves, start with Ampère's law,

$$\nabla \times H = J + \tfrac{\partial D}{\partial t} = \sigma E + \sigma V \times B + J^e + \tfrac{\partial D}{\partial t} \qquad (11)$$

Now assume time-harmonic fields and use the definitions of the potentials, $B = \nabla \times A,\ E = -\nabla V - \tfrac{\partial A}{\partial t}$, and combine them with the constitutive relationships $B = \mu_0 (H + M)$ and $D = \varepsilon_0 E + P$ to rewrite Ampère's law as:

$$\begin{aligned}&(j\omega\sigma - \omega^2 \varepsilon_0) A + \nabla \times (\mu_0^{-1} \nabla \times A - M) \\ &- \sigma V \times (\nabla \times A) + (\sigma + j\omega\varepsilon_0) \nabla V = J\end{aligned} \qquad (12)$$

In the 2D in-plane case there are no variations in the z-direction, and the electric field is parallel to the z-axis. Therefore you can write ∇V as −ΔV/L where ΔV is the potential difference over the distance L.

Now simplify these equations to:

$$\begin{aligned}&-\nabla . (\mu_0^{-1} \nabla A_z - \begin{bmatrix} -M_y \\ M_x \end{bmatrix}) + \sigma V . \nabla A_z \\ &+ (j\omega\sigma - \omega^2 \varepsilon_0) A_z = \sigma \tfrac{\nabla V}{L} + J_\varphi^e + j\omega P_\varphi\end{aligned} \qquad (13)$$

Where: σ electrical conductivity, V_{loop} loop potential, J_φ^e external current density, P_φ electric polarization, A_z magnetic potential z component and v is velocity.

With using finite element mode performs this transformation to avoid singularities on the symmetry axis.

The relevant interface condition is $n_2 \times (H_1 - H_2) = J_\varphi$

The natural boundary condition fulfills this equation if the surface current vanishes. We can transform the Neumann condition of this PDE into:

$$- n.[(\mu_0^{-1}\nabla A_z - \begin{bmatrix} -M_y \\ M_x \end{bmatrix})_1 - (\mu_0^{-1}\nabla A_z - \begin{bmatrix} -M_y \\ M_x \end{bmatrix})_2$$
$$= -n \times [(\mu_0^{-1}\nabla \times A - M)_1 - (\mu_0^{-1}\nabla \times A - M)_2] \quad (14)$$
$$= -n \times (H_1 - H_2) = 0$$

Joule Equations:

$$-\nabla.(\delta\nabla V - J^e) = Q \quad \text{and} \quad \delta = 1/(\rho_0(1+\alpha(T-T_0)))$$

$$n.(J_1 - J_2) = \delta(V - V_{ref})/d \quad (15)$$

Where: V is potential is around of 66 volts, δ is conductivity at reference temperature and d is thickness.

5. Simulation in COMSOL software

The simulations of temperature distribution have done on base of many cases. Element length, diameter and distance between elements- element with reflector wall and bottom; depth and dimensions of reflector, reflector material (material of surface, insulation and back of reflector), and design of reflector, power and sealed system are important in temperature distribution and so losses. Low losses and have high temperature efficiency in 20 centimeter in top of element is the aim of this simulation. Necessary data for simulation has been given in table 1,2 and figures 2,3,4 and 6.

6. Result an discussion

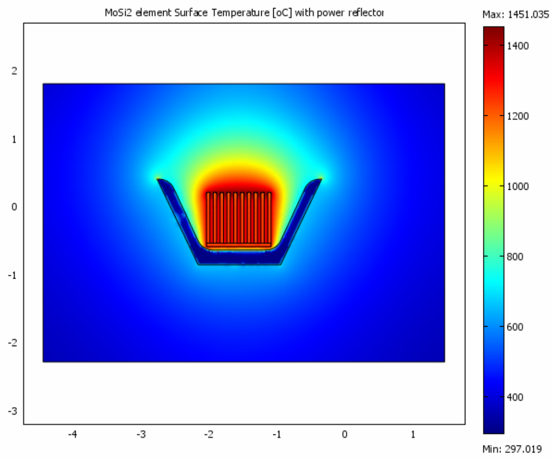

Figure 7. Simulation of temperature distribution in bowel form reflector in 500A current

Table 3. Simulation results

Parameter	Descriptions			
Emistivity	0.7	0.85	0.7	0.85
Reflector shape	cave	Cave	circle	circle
a[mm]	80	80	80	80
L_e[mm]	200	200	200	200
Depth[mm]	230	230	230	230
Element tmp.[ºk]	1900	1900	1900	1900
Simulated tmp.[ºk] on 20cmre	1720	1745	1795	1820

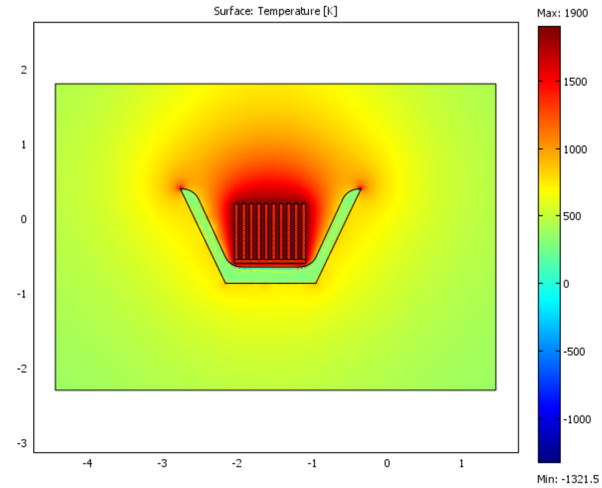

Figure 8. Simulation of temperature distribution in bowel form reflector in 605 A

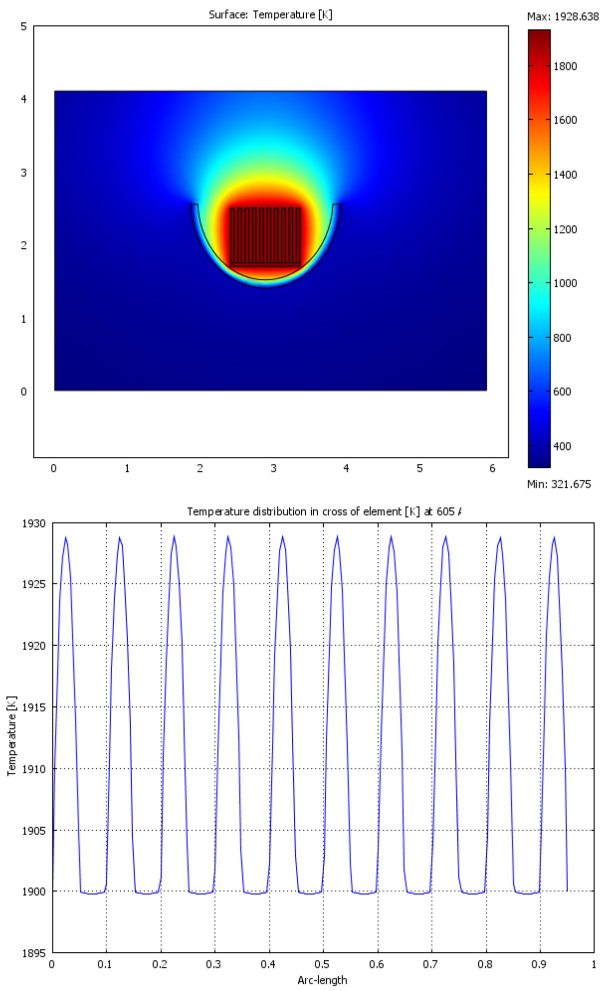

Figure 9. Simulation of temperature distribution in circular

form reflector in 605 A current and the Temperature distribution on element is drawn in down figure

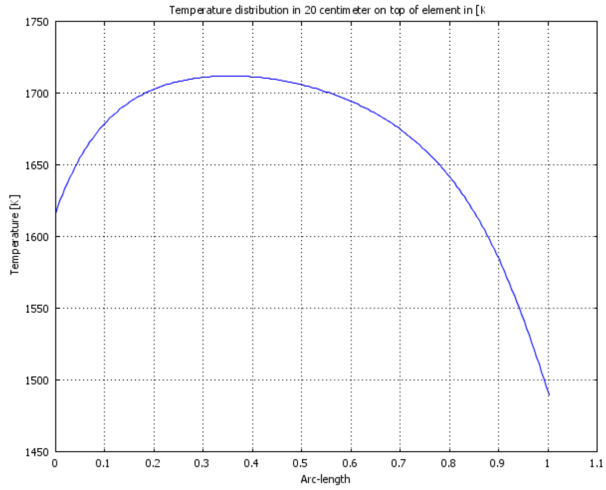

Figure 10. Simulation of temperature distribution in bowl form reflector in 605 A current at 20 centimeter on the top of element

In figures 7-10 the temperature distribution in bowl and circular reflector forms are shown. The summary results have written in table3. In these results illustrated that circular reflector on his fireplace has a high efficiency on temperature profile. And so in figure 11- 13 electrical field and temperature distribution are shown.

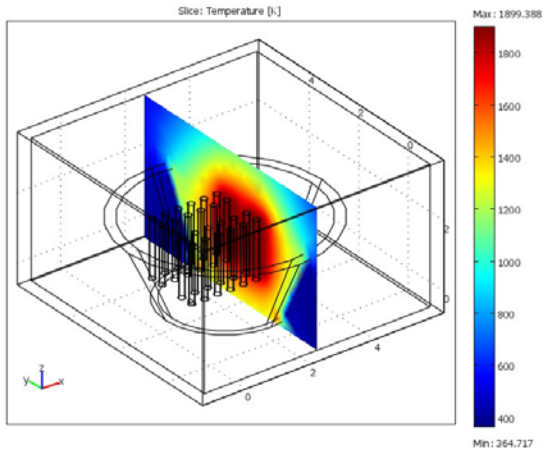

Figure 11. Simulation of temperature in Cone form reflector on 605 A current

7. Conclusion

These simulations indicate that the emissivity of the work piece has to be considered in addition to its thermal mass. Necessary distance, between elements, to counteract the effect of the electromagnetic force on elements must be kept; in this case, with increasing in the surface loading and so element length, the distance must be increased. Accessible area for element installation, element dimension and element location has shown that has a responsible effect on temperature distribution. In elliptical and circular reflectors, if 20 cm line will have located in the fireplace, on that's case, it will have higher efficiency.

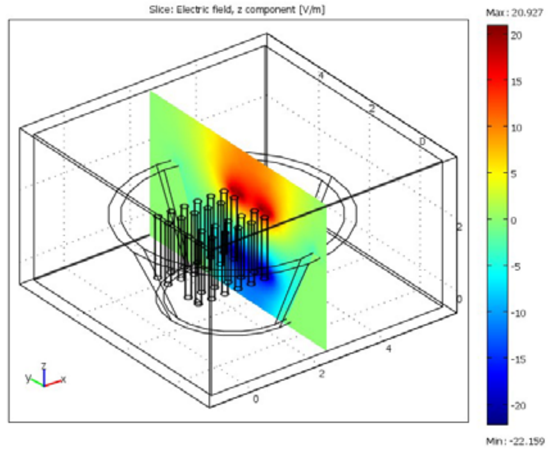

Figure 12. Simulation of Z direction electrical field in Cone form reflector on 605 A current

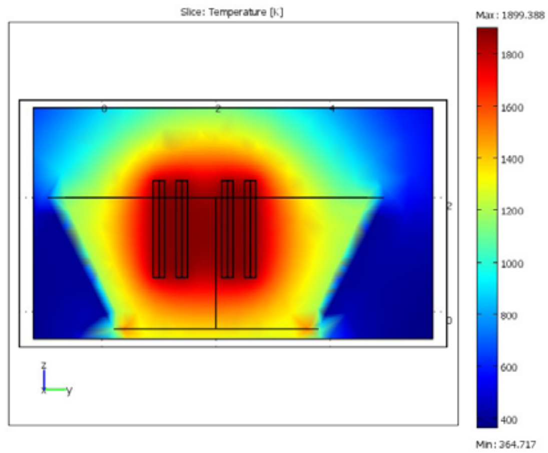

Figure 13. Simulation of temperature in Cone form reflector on 605 A current, 2D of figure 11

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