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 1800ºC. 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 MoSi2 elements are graded in many maximum temperature ranges, same 1700ºC (3090°F) and 1850ºC (3270°F). Elements are available in many shapes and forms (see examples shown below).

Benefits of MoSi2 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 gradually 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 (MoSi2) 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/m² 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 °C respectively; power density is 110 w/m² 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 ε = 0.7

Figure 2. Thermal conductivity (W/m K)versus temperature
Table 1. Element for 12mm hot zone diameter and fiber panel characterizes

<table>
<thead>
<tr>
<th>Element</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of shanks</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>Hot zone length, Le (mm)</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Terminal length, Lu (mm)</td>
<td></td>
<td>150 mm for 12 mm hot zone.</td>
</tr>
<tr>
<td>Center-to-center distance, a (mm)</td>
<td>35/45</td>
<td>60/80</td>
</tr>
<tr>
<td>Hot zone diameter, d (mm)</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Terminal diameter, c (mm)</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Surface load (W/cm²)</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Current (A)</td>
<td>200</td>
<td>700</td>
</tr>
<tr>
<td>Plug and Fiber panel</td>
<td></td>
<td>605</td>
</tr>
<tr>
<td>Material quality</td>
<td>1400</td>
<td>1700</td>
</tr>
<tr>
<td>Shape</td>
<td>600<em>600</em>230mm</td>
<td></td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>100w/m²k⁴</td>
<td></td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Coefficient of radiation</td>
<td>5.67w/m²°C</td>
<td></td>
</tr>
</tbody>
</table>

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

Figure 4. Resistivity (Ωm) versus temperature

Table 2. Technical data of reflectors

<table>
<thead>
<tr>
<th>Classification/Service Temperature</th>
<th>1600°C/1500°C</th>
<th>2912°F/2732°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>300 kg/m³</td>
<td>18.6 lb/ft³</td>
</tr>
<tr>
<td>LOI (°C/6h)</td>
<td>KVS 161 4%</td>
<td>KVS 164 0%</td>
</tr>
<tr>
<td>Linear Thermal Shrinkage (KVS 161)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 1300°C (2372°F)</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>@ 1400°C (2552°F)</td>
<td>-1.0%</td>
<td></td>
</tr>
<tr>
<td>@ 1500°C (2722°F)</td>
<td>-1.5%</td>
<td></td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>0.15 MPa</td>
<td></td>
</tr>
<tr>
<td>@ 10% compression</td>
<td>21.9 lb/in²</td>
<td></td>
</tr>
<tr>
<td>Cold Bending Strength (MOR)</td>
<td>1 Mpa</td>
<td>146 lb/in²</td>
</tr>
<tr>
<td>(3 Point Bend)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.92 J/g°C</td>
<td>0.22 BTU/lb°F</td>
</tr>
</tbody>
</table>
4. The Heat Equation

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

\[ \rho C_\frac{dT}{dt} + \nabla \cdot (-KT) = Q \]

Quickly review the variables and quantities in this equation:

- \( T \) is the temperature.
- \( \rho \) 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 \( \rho \) 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:

\[ \rho C_p \frac{dT}{dt} + \nabla \cdot (-KT + \rho C_p Tu) = Q \]

(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:

\[ q = -KVT + \rho C_p Tu \]

Where: \( q \) is the heat flux vector. If the heat transfer is by conduction only, \( q \) is determined by:

\[ q = -KVT \]

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:

\[ -n \cdot q = q_0 \]  

(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:

\[ -n \cdot q = q_0 + h(T_{inf} - T) \]  

(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:

\[ J = \rho G + \varepsilon \sigma T^4 \]  

(4)

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

\[ q = G - J \]  

(5)

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

\[ q = (1 - \gamma)G - \varepsilon \sigma T^4 \]  

(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:

\[ \varepsilon = \gamma \]  

(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:

\[ q = \varepsilon(G - \sigma T^4) \]  

(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 \( T_{amb} \).

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:

\[ G = \sigma T_{amb}^4 \]  

(9)

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

\[ q = \varepsilon \sigma(T_{amb}^4 - T^4) \]  

(10)

4.6- Electromagnetic equations:

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

\[ \nabla \times B = J + \frac{j \omega}{\mu} \]  

(11)

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

\[ j \omega \sigma - \omega^2 \varepsilon \sigma \nabla \times \left( \mu \varepsilon \nabla \times A - M \right) - \sigma \nabla \times (\nabla \times A) + (\sigma + j \omega \varepsilon) \nabla V = J \]  

(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 \( \nabla V = -\Delta V/L \) where \( \Delta V \) is the potential difference over the distance \( L \).

Now simplify these equations to:

\[ -\nabla \left( \mu \sigma \nabla A_z - \frac{M_z}{M_z} \right) + \sigma \nabla \cdot A_z \]

\[ + (j \omega \sigma - \omega^2 \varepsilon \sigma) A_z = \sigma \varepsilon \nabla \cdot J_z + j \omega P_z \]

Where: \( \sigma \) electrical conductivity, \( V \) loop potential, \( J_z \) external current density, \( P_z \) 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 \( n_z \times (H_1 - H_2) = J_z \)

The natural boundary condition fulfills this equation if the surface current vanishes. We can transform the Neumann condition of this PDE into:
- \eta \left[ \left( \frac{\mu}{M} \right) \nabla A - \left( \frac{M}{\mu} \right) \nabla \phi \right] = -n \left[ \left( \frac{\mu}{M} \right) \nabla A - \left( \frac{M}{\mu} \right) \nabla \phi \right] : \left( \frac{\mu}{M} \right) \nabla A - \left( \frac{M}{\mu} \right) \nabla \phi \right] = -n \left( \left( H_1 - H_2 \right) = 0 \right) \tag{14}

Joule Equations:
\[ -\nabla (\delta V J) = Q \quad \text{and} \quad \delta = \sqrt{\left( \rho_0 (1+\alpha(T-T_0)) \right)} \]
\[ n(J_1 - J_2) = \frac{\delta(V - V_{ref})}{d} \tag{15} \]

Where: \( V \) is potential is around of 66 volts, \( \delta \) 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

<table>
<thead>
<tr>
<th>Depth[mm]</th>
<th>230</th>
<th>230</th>
<th>230</th>
<th>230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element temp.[°k]</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
</tr>
<tr>
<td>Simulated temp.[°k] on 20cmre</td>
<td>1720</td>
<td>1745</td>
<td>1795</td>
<td>1820</td>
</tr>
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</table>

Table 3. Simulation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emistivity</td>
<td>0.7 0.85 0.7 0.85</td>
</tr>
<tr>
<td>Reflector shape</td>
<td>cave Cave circle circle</td>
</tr>
<tr>
<td>d[mm]</td>
<td>80 80 80 80</td>
</tr>
<tr>
<td>L_e[mm]</td>
<td>200 200 200 200</td>
</tr>
</tbody>
</table>

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

Figure 9. Simulation of temperature distribution in circular

Figure 7. Simulation of temperature distribution in bowel form reflector in 500A current
form reflector in 605 A current and the Temperature
distribution on element is drown 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 table 3. 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 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.

**References**

1. KANTHAL super electric heating element hand book
2. COMSOL Multiphysics version 3.3a software

Kourosh Mousavi Takami was born in Sari, Mazandaran, Iran. He received the B.S.c. degree in electric power engineering from the Iran University of Science and Technology (IUST) Tehran, Iran, Oct 1995 and the M.Sc. degree in electric power engineering from the Engineering Faculty of Mazandaran University, Iran in 2002. Currently, he is PhD student at Mälardalen University in Sweden since 2005. He has so over ten years experience in power system design and installations. His research interests include Optimization and simulation of heat generation and transfer in the core and winding of power transformers; diagnostic testing and condition monitoring of power equipments, and application of fuzzy and Ants algorithm to condition monitoring of power equipments.