DETERMINATION OF REFRACTORY LINING THICKNESS OF STEEL PLANT MIXER FURNACE

István SZŰCS  Prof. Dr.; Tamás KOÓS, Ph.D. student

University of Miskolc, faculty of Materials Engineering, Institute of energy and quality assurance, H-3515 Miskolc-Egyetemváros, Hungary; tuzsi@uni-miskolc.hu

Abstract
The refractory wall of a steel plant mixer furnace becomes worn out under the erosion and corrosion influence of molten pig iron and slag. As the lining becomes thinner the heat losses of the mixer increase. The unexpected holes of the unevenly thinned refractory wall pose an especially big danger since the leaking pig iron and slag can cause operating trouble, explosion, fire or tragic accidents. In order to examine the actual wall thickness of 1500 t pig iron tilting mixer furnace, thermovision is applied at DUNAFERR Steel Plants Ltd. It has been established that on the basis of temperature field of the outside armor plate one can estimate the actual conditions of the wall. The correct estimation of the smallest wall thickness is expected as a result of coupling thermovision with finite element modeling of the heat transport processes. The aim of this research is to elaborate a computational method where the actual thickness of the lining can be determined without the removal of the molten pig iron. By calculation the thickness of the wall from the outside temperature distribution the companies will have adequate time for the repair of refractory wall by torkreting of magnesia, or for the decision of stopping the equipment in case the dangerous degree thinned of refractory wall.

Key words: mixer furnace, refractory materials, wall thickness

1. INTRODUCTION
Refractory wall of high temperature equipment used in industry plays an important role in technological processes. Abrasive forces, chemical corrosion, effecting on internal working refractory materials, thermal and mechanical stresses during operation cause the fast and unequal thinning down in certain areas of the lining of the industrial furnaces. The refractory lining of the industrial furnaces has to fulfill the following tasks: decrease or eliminate the effects disturbing the heat production and manufacturing; ensure the conditions necessary for the heat production and the combustion reactions; establish the optimum heat transport conditions necessary for the technological processes; resist the physical and chemical effects of the additives and the melt charge; take up the thermal and mechanical stresses caused by the production processes. The heat loss and the wall thickness are in direct relationship. Unexpected holes of the unevenly thinned refractory wall of hot metal pig iron mixer pose an especially big danger since the leaking pig iron and slag can cause operating trouble, explosion, fire or tragic accidents. Safe operation of furnaces of molten materials and increase of their lifetime can be achieved by regular – in operation – repair of the quickly wearing wall parts. The thickness of a steel plant pig iron mixer’s lining cannot be observed visually during operation therefore the timing and the area of repair is usually determined by local experience based on the wall’s outside temperature. Primary goal of our research was the elaboration of a diagnostic method for the determination of the critically thinned down of refractory lining of pig iron mixer furnace in steel plant.

2. CHARACTERISTICS OF EXAMINED PIG IRON MIXER FURNACE
The outer diameter of the horizontal cylindrical pig iron mixer furnace is 7,6 m and its longitudinal dimension reaches up to 12 meters Fig. 1. The Fig. 2 shows the cross section and inside photo of the opened 1300 t pig iron mixer furnace after two years of operation in ISD DUNAFERR Steel Plants Ltd. By examining the images it is readily observable that the internal working refractory layer is substantially thinned at the level of molten pig iron. A huge slag deposit on front and back sides of the furnace is decreasing the volume above the liquid metal line. The weighty slag bear causes enormous tensile and bending stresses in the magnesite brick layer during tilting of
the furnace. The effects of destructive forces and processes cause fast and unequal thinning of the furnace lining at the level of pig iron.

**Fig 1.** Longitudinal-vertical section of the examined 1300 t pig iron mixer. Maximum outer diameter 7.6m, minimum inner and longitudinal dimension reaches up to 12 meter

**Fig 2.** Vertical cross-section of mixer and photo taken about dismantled refractory line at the end of campaign, after two years working

Photo of weared refractory wall
1 – Slag bear on the wall
2 – Dangerously thinned wall
3 – Bottom 4- Armour plate
3. INSTRUMENTATION OF MEASURED TEMPERATURE FIELD OF MIXER OUTSIDE SURFACE

An advanced method for the measurement of the thickness of melting equipment for example at basic oxygen furnace is the use of laser based profile measurement instruments. In this case the molten material has to be emptied out of the bath before measurement can be made. Thus the method cannot be applied for the examination of the most dangerous surfaces of equipment continuously filled with molten material i.e., the thickness of lining cannot be measured in pig iron mixer furnaces below the liquid metal level. The wall thickness of furnaces working with molten metal we can determine from the temperature field on the outer side surface of furnace armour (Fig. 3).

The outside temperature distribution of the pig iron mixer is determined using an AGEMA Thermovision LWB 880 system. The thermovision images can be evaluated using a PC based CATS-E 2.0 software. These images show the temperature distribution that will be the basic input parameters for the finite element method for computing of wall thickness.

![Thermovision Images](image)

**Fig 3.** Stationer temperature filed measured with Thermovision at the back side wall of the 1300 t pig iron mixer after one week (beginning of campaign) and after two years working (at end of campaign)

4. THEORETICAL BACKGROUND OF MATHEMATICAL MODEL FOR THE HEAT TRANSFER

The geometry is a layered structure cylindrical furnace wall, where we search for the solution of the thermo-diffusion differential equation for steady-state temperature $T(x,y,z)$ distribution. The thermovision data acquisition, which is the experimental base of our analysis, is carried out when the transient processes had attenuated and quasi-static state can be considered [1].

So the equation of heat transfer is the following:
\[ \nabla (\lambda \cdot \nabla T) = Q \quad \text{in} \quad \Omega \]  

where \( \nabla \) is the gradient operator, \( \lambda(x, y, z) \) is the isotropic thermal conductivity that depends on temperature and layer of refractory wall, while \( \Omega \) is the volume of the analyzed wall segment. In our case there is no internal heat generation, so \( Q = 0 \) is assumed. The thermal and transport boundary conditions are the following:

**Dirichlet type:**

\[ T = \tilde{T}(s, t) \quad \text{on} \quad \Gamma_T \quad \text{for} \quad t > 0 \]  

where \( s \) denotes the coordinate of a node on the inner surface \( \Gamma_T \) of the furnace wall.

The inner temperature was fixed by the molten pig iron to 1340 °C.

**Neumann type:**

\[ \tilde{n} \cdot (\lambda \cdot \nabla T) + q_c + q_r = 0 \quad \text{on} \quad \Gamma_q \quad \text{for} \quad t > 0 \]  

where \( \tilde{n} \) is the normal of the outer surface \( \Gamma_q \) with

\[ q_c = \alpha_c(s) \cdot (T - T_c) \]  

and

\[ q_r = \alpha_r(s) \cdot (T - T_r) \]  

convective and radiative heat transfer components with respect to \( T_c \) and \( T_r \), sink temperature (are the same, 20 °C). In our model the \( \alpha_c(s) \) convective heat transfer coefficient on the outer side of the furnace was taken as a function of the Nusselt number, while it was independent of temperature and time and were uniform over the inner surface. The effective radiative heat transfer coefficient is the following:

\[ \alpha_r = F \cdot \sigma \cdot (T + T_r) \cdot (2T^2 + T_r^2) \]  

where \( \sigma \) is the Stefan-Boltzmann constant, \( F \) is a form factor including the boundary emissivity, \( \varepsilon(s) \), and the position (view factor) of the radiating finite areas relative to each other. The \( \varepsilon(s) \) was considered time and temperature independent but the local variation of it is an important influencing factor on the outer temperature map that was recorded. The view factor terms were calculated during a FEM pre-process using an usual formula:

\[ F_{i-j} = \frac{1}{A_k} \int \int \frac{\cos \Theta_k \cos \Theta_j}{\pi \cdot R^2} dA_j dA_k \]  

where \( R \) is the distance from a point on a surface \( A_j \) to a point on a surface \( A_k \). The angles \( \Theta_j \) and \( \Theta_k \) are measured between the line \( R \) and the normal to the surface. The other surfaces of the block of the furnace wall were isolated or the boundary condition \( \tilde{n} \cdot (\lambda \cdot \nabla T) = 0 \) was required. Since the material interfaces \( i \) and \( j \) (INT) of the layered structure appeared inside the wall, usual continuity conditions on temperature and heat flux were satisfied automatically by the FEM treatment [2].

The governing formula is the following:
\[ \bar{n}(\lambda_j \cdot \nabla T)_{\text{INT}} - \bar{n}(\lambda_j \cdot \nabla T)_{\text{INT}} = 0, \quad \text{and} \quad T_i|_{\text{INT}} = T_j|_{\text{INT}} \]  

(8)

The initial condition on the temperature was set up as: \( T(s, t=0) = T_0(s) \).

This mathematical model can describe the real situation of heat exchange processes in case of different refractory wall thickness of pig iron mixer furnace. These equations may include changing the boundary condition to convective heat transfer at the inner wall of furnace [3], the heat conductivity coefficient of refractory materials depending on temperature and relate the \( q_c \) outer heat transfer coefficients to the environmental air properties.

5. RESULTS OF THE SOLVING OF THE MATHEMATICAL MODEL FOR THE HEAT TRANSFER AND WALL THICKNESS

The basic geometrical dimensions and thermal technical data of refractory lining for solving of mathematical model of pig iron mixer are summarized in Table 1.

Table 1. Geometry and material parameters of refractory lining of the 1300 t pig iron mixer furnace.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Magnesite brick</td>
<td>Magnesitepowder</td>
<td>Magnesite brick</td>
<td>Magnesite powder</td>
<td>Chamot brick</td>
<td>Chamot gravel</td>
<td>Steel shield</td>
</tr>
<tr>
<td>Inner radius (m)</td>
<td>2,785</td>
<td>3,360</td>
<td>3,375</td>
<td>3,525</td>
<td>3,535</td>
<td>3,659</td>
<td>3,759</td>
</tr>
<tr>
<td>Wall thickness (m)</td>
<td>0,575</td>
<td>0,015</td>
<td>0,150</td>
<td>0,010</td>
<td>0,125</td>
<td>0,100</td>
<td>0,060</td>
</tr>
<tr>
<td>Number of sublayers</td>
<td>15</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Heat conductivity (W/mK)</td>
<td>7,7 (500 °C)</td>
<td>5,9 (750 °C)</td>
<td>4,6 (1000°C)</td>
<td>3,8 (1200°C)</td>
<td>3,5 (1400°C)</td>
<td>1,0</td>
<td>1,0</td>
</tr>
<tr>
<td></td>
<td>6,4 (750 °C)</td>
<td>6,4 (750 °C)</td>
<td>5,0 (1000°C)</td>
<td>4,2 (1200°C)</td>
<td>1,0</td>
<td>1,16 (500°C)</td>
<td>1,20 (600°C)</td>
</tr>
<tr>
<td></td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
<td>1,16 (500°C)</td>
<td>1,35 (1000°C)</td>
<td>1,35 (1000°C)</td>
<td>1,40 (1160°C)</td>
</tr>
<tr>
<td></td>
<td>0,4 (200 °C)</td>
<td>0,4 (200 °C)</td>
<td>0,4 (200 °C)</td>
<td>0,4 (200 °C)</td>
<td>30 (160 °C)</td>
<td>30 (160 °C)</td>
<td>30 (160 °C)</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>3020</td>
<td>750</td>
<td>3020</td>
<td>750</td>
<td>4000</td>
<td>600</td>
<td>7800</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>1172</td>
<td>1172</td>
<td>1172</td>
<td>1172</td>
<td>1100</td>
<td>754</td>
<td>502</td>
</tr>
</tbody>
</table>

The mathematical model of heat exchange processes for mixer furnace was solved by Finite Element Method. We calculated the temperature distribution on the outside surface of the mixer armour for some wall thickness. As an example is shown the temperature field on armour of mixer in case of 370 mm refractory thickness of furnace in Fig 4. Calculated by FEM stationer temperature distribution on the outside surface of back side wall in some cases of wall thickness (v=270, 370, 425, 500 mm; dimension of worn line w=765, 660, 610, 535 mm) we can see in Fig 5.

6. INDUSTRIAL RESULTS OF THE WALL THICKNESS DETERMINATION

The Fig 6, shows the measured after two years working (at end of campaign) and calculated wall thickness of mixer, determined by mathematical model from maximum temperature on the outside surface of back side wall of furnace. We can see, that the difference between calculated, and measured wall thickness is only 40 mm. In our researches we examined the temperature field of surface of mixer during two campaigns. In case of second campaign, the repair time of refractory wall was determined from lining thickness, calculated from outside temperature by equation (9), where \( T \) in °C denotes the temperature of armour, measured by Thermovision [4].

\[ T_{\text{arm}} = \frac{T_{\text{env}}}{2} + 100 \]  

(9)
The industrial results (Fig. 7) show, that in case of second campaign wall repairing increase by 25 % the mass of stored pig iron, yield 20 % furnace life time growth and 37 % sawing in refractory costs.

**Fig 4.** Calculated temperature (K) field on the outside surface of back side wall of the 1300 t pig iron mixer in case of 370 mm wall thickness (worn refractory lining thickness 665 mm)

**Fig 5.** Calculated stationer temperature distribution on the outside surface of back side wall in some cases of wall thickness (v=270, 370, 425, 500 mm)
Fig 6. Measured and calculated wall thickness of mixer furnace, determined by mathematical model from maximum outside surface temperature of armour.

Fig 7. The industrial results of wall thickness determination and refractory reparation in relative value of basic campaign.

We can establish, that the method of wall thickness calculation on basis of measured surface temperature is a sure and economical method for the pig iron mixer furnace.

REFERENCES