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Determining the Thermal Parameters of Complex Furnace Linings

Cooling furnace walls to reduce the hot face temperature of the lining enables a stable accretion layer to form that protects the refractory and potentially increases the campaign length. However, establishing the optimum cooling system and refractory lining requires a thorough understanding of the heat fluxes through different furnace walls. To provide data and enable the heat fluxes through a complex furnace lining to be modelled, an experimental furnace wall was developed to simulate in service conditions. Subsequently, the data obtained from the experimental analyses was used in computational fluid dynamic (CFD) modelling to enable the heat flow to be accurately modelled for a spray cooled complex furnace lining.

Introduction

The increasing requirement for high performance furnaces in the metal industries has resulted in the increased use of partially water cooled furnaces that require complex furnace linings. Currently, multiple cooling systems are available on the market, including various water cooled systems (e.g., spray cooling, cooled copper blocks, and ripple cooling) and air cooled systems [1]. The water cooling mechanisms enable the hot side temperature of the furnace to be reduced, and thereby the melt forms a protective accretion layer on the refractory surface that decreases refractory wear and increases the furnace lining campaign lifetime.

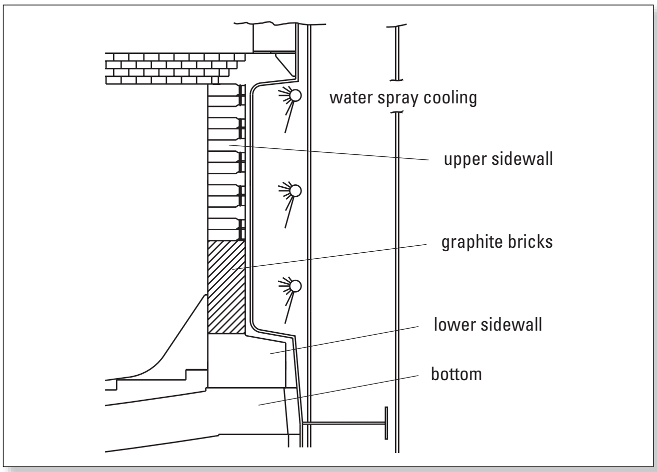

Figure 1. *Cross section through the bottom and side wall lining of the ferronickel electric furnace at FENI (Kavadarci, Macedonia).*

The cooling systems, in particular those using water, are designed to handle high heat fluxes; however, the heat flow through the lining is also a function of the furnace temperature, the different wall material heat conductivities, the heat transfer coefficients, and the lining thicknesses. If the lining thermal conductivity is low, insufficient heat is conducted through the bricks resulting in high refractory infiltration and a subsequent increase in the thermomechanical load. This results in refractory corrosion problems due to chemical attack by the liquid metal or slag on the surface and within the bricks, as well as expansion of the bricks due to the internal formation of new phases. However, using water-cooled systems without any refractory is not an option because of the high heat and energy losses that make this type of furnace design uneconomical. Therefore, it is essential to determine the optimum combination of refractories and cooling devices to enable effective wall cooling.

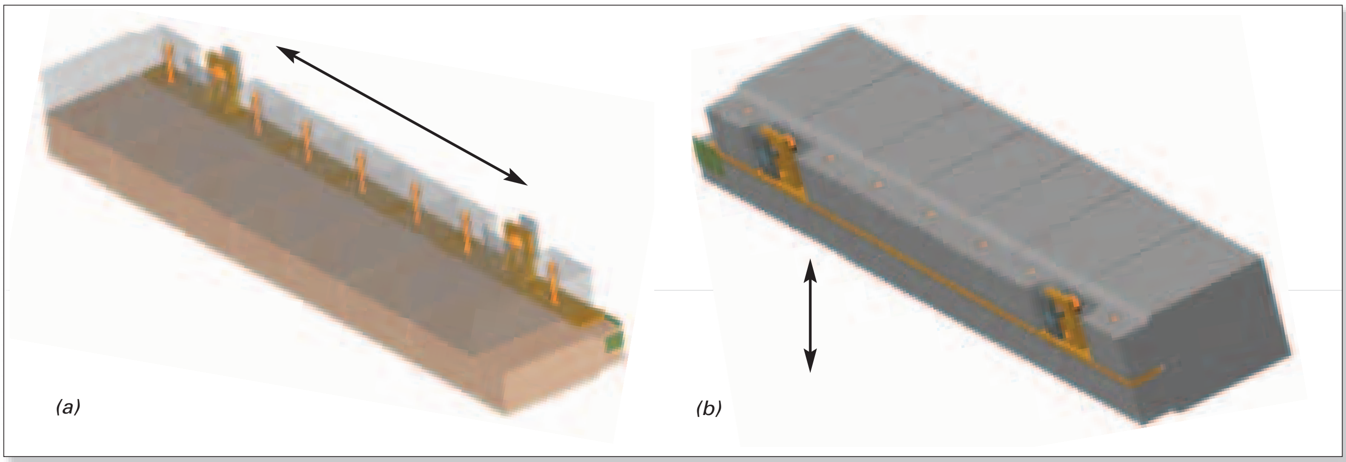

Figure 2. *Hanging system for the ANKER T15 bricks, (a) front view and (b) rear view illustrating the option for horizontal and vertical movement.*

Currently, investigations into the thermal and thermomechanical behaviour of various furnace linings are being performed at the RHI Refractories Technology Center, Leoben, Austria, in cooperation with the Christian Doppler Laboratory for Secondary Metallurgy of the Non-Ferrous Metals, University of Leoben, Austria.

Initially, calculations of the heat fluxes through test walls were performed using a simple one-dimensional mathematical model. This model used the electrical resistance analogy, as described in equation 1:

$$k = \frac{1}{\frac{1}{\alpha_i} + \Sigma \frac{s_j}{\lambda_j} + \frac{1}{\alpha_a}} \qquad (1)$$

where k is the heat transition coefficient [W/m²K], α_i is the heat transfer coefficient at the hot face [W/m²K], α_a is the heat transfer coefficient at the cold face [W/m²K], λ_j is the different wall material heat conductivity coefficients [W/mK], and s_j is the different wall material thicknesses. However, there are a number of variables involved in this calculation that are not known or not well established and these vary with temperature. Therefore, it was very difficult to determine exact results using this calculation. Some of the most important variables are the heat transfer coefficients and the hot face temperatures. In addition, there are three-dimensional effects, due to the nonhomogeneous test area, that can not be included in a one-dimensional model.

To enable a furnace lining to be modelled by three-dimensional CFD calculations it was necessary to experimentally determine specific heat data relating to a particular furnace lining. Therefore, an experimental furnace test wall was installed at the RHI Refractories Technology Center to enable these values to be determined under in service simulated test conditions. The experimental equipment included a vertical test wall that was designed to simulate part of a furnace wall. Different refractory materials could be attached to the wall that was directly heated and cooled. Subsequently, using the measured data, it was possible to create a CFD model of the complex furnace wall [2].

Experimental Design

In the first test series, the furnace side wall of the ferronickel electric furnace at FENI (Kavadarci, Macedonia) was simulated (Figure 1). ANKER T15 bricks (tar-soaked magnesia bricks) were used at the top and graphite bricks were used in the bottom region of the test wall lining. At the top of the wall, the ANKER T15 bricks were affixed to the steel shell using a recently developed hanging system (RHI Non-Ferrous Metals Engineering GmbH, Leoben, Austria) (Figure 2). This system enables the bricks to move evenly in both a vertical and horizontal direction during the heating up process. In the lower part of the test wall, the graphite bricks were installed and adjusted to the required distance from the steel shell using an alternative hanging system (RHI Non-Ferrous Metals Engineering GmbH, Leoben, Austria) (Figure 3) that enables vertical brick movement during the furnace heat up.

To guarantee effective contact between the steel shell and bricks, the graphite based ramming mix termed Sigri RST16 was used. This mix is characterized by a high heat conductivity. Sequentially, the gap between the steel shell and two brick lines was filled with the Sigri RST16 ramming mix (240 mm) and vertically compressed to 145 mm (40% compression). In the region where the hanging system was attached to the wall, the mix was only poured and not compacted, to ensure free movement of the attached bar (Figure 4 and 5).

A propane/oxygen burner with a maximum thermal output of 150 kW was used to heat the 1.2 m² test wall and temperatures of up to 1500 °C were achieved. To measure the temperature distribution through the lining, thermocouples were installed at defined distances through the wall within the different materials. The wall was spray water cooled from the back, as in the original FENI furnace (see Figure 1), and the volume and temperature of water used for cooling was recorded throughout the experimental run. Therefore, the heat dissipation using the water spray cooling could be calculated. This value of heat flow provides information about when an accretion layer would start to freeze on the refractory.


(a) (b)

Figure 3. *Graphite block hanging system. (a) Attachment to the furnace steel shell and (b) schematic diagram illustrating the option for vertical movement.*

Figure 4. Hanging bar.

Figure 5. Hanging system with the formwork to pour in the Sigri RST16.

During the test trials, the wall was insulated from the environment using a highly isolating material. The furnace chamber was attached to the bricks and the wall was heated to approximately 1500 °C within the chamber. The test wall and experimental equipment is illustrated in Figures 6 and 7.

The yellow line in Figure 6 denotes the experimental region that was directly heated and the individual markings indicate the bricks that were equipped with thermocouples.

Determination of the Test Wall Temperature Distribution

To determine the temperature distribution through the test lining, the ANKER T15 bricks, graphite bricks, ramming mix, and steel shell were equipped with thermocouples. The total lining thickness was 443 mm, which comprised of 375 mm of ANKER T15 brick or 375 mm of graphite brick, 60 mm of Sigri RST16, and 8 mm of steel shell. In multiple planes, five thermocouples were distributed through the refractory brick at 0 mm (hot face), 55 mm, 125 mm, 225 mm, and 325 mm from the hot face; one was located within the ramming mix (405 mm from the hot face); and the inlet and outlet cooling water temperature was recorded. The temperature distributions through the different test wall materials during heating are detailed in Figures 8 and 9.

Using the experimental data and the water balance, the heat transfer coefficients at the hot face and at the cold face (from the steel shell to the water cooling) were calculated [3]. Furthermore, other data was calculated from the recorded temperatures for the subsequent CFD modelling.

CFD Modelling

Calculating the heat and temperature distribution is possible if the physical laws governing energy flow can be expressed as differential equations. Each single differential equation is linked to specific laws and consists of one physical value that is a dependent variable. An example of a dependent variable is the specific enthalpy/energy. The temperature, which is often given as a dependent variable, is not a specific value because it is combined in a fundamental equation with the energy/enthalpy equation (2) [4]:

$$\frac{\partial \rho h}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j h\right)=\frac{\partial}{\partial x_j}\left[\frac{\lambda}{c_p}\frac{\partial h}{\partial x_j}\right]+\frac{\partial p}{\partial t} \qquad (2)$$

where ρ is the density, p is the pressure, λ is the thermal conductivity, c_p is the specific heat at a constant pressure, x is the direction, h is the enthalpy, and t is the time.

Figure 6. Test wall.

Figure 7. Experimental concept.

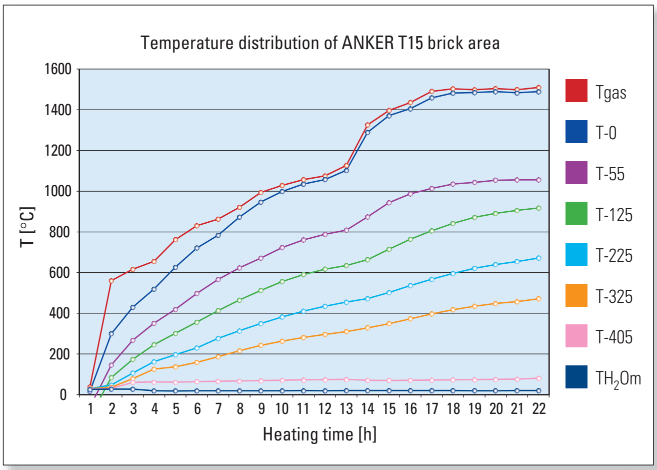

Figure 8. *Temperature distribution through the lining in the ANKER T15 brick area. Tgas was the gas temperature within the furnace chamber; T-0 was the brick hot face temperature; T-55, T-125, T-225, T-325, and T-405 were the temperatures 55 mm, 125 mm, 225 mm, 325 mm, and 405 mm, respectively, from the hot face; and* TH_2Om *was the average of the inlet and outlet water cooling temperature.*

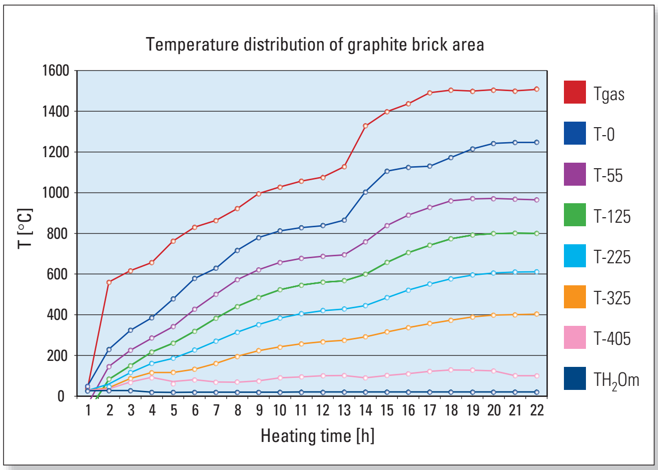

Figure 9. *Temperature distribution through the lining in the graphite brick area. Tgas was the gas temperature within the furnace chamber; T-0 was the brick hot face temperature; T-55, T-125, T-225, T-325, and T-405 were the temperatures 55 mm, 125 mm, 225 mm, 325 mm, and 405 mm, respectively, from the hot face; and* TH_2Om *was the average of the inlet and outlet water cooling temperature.*

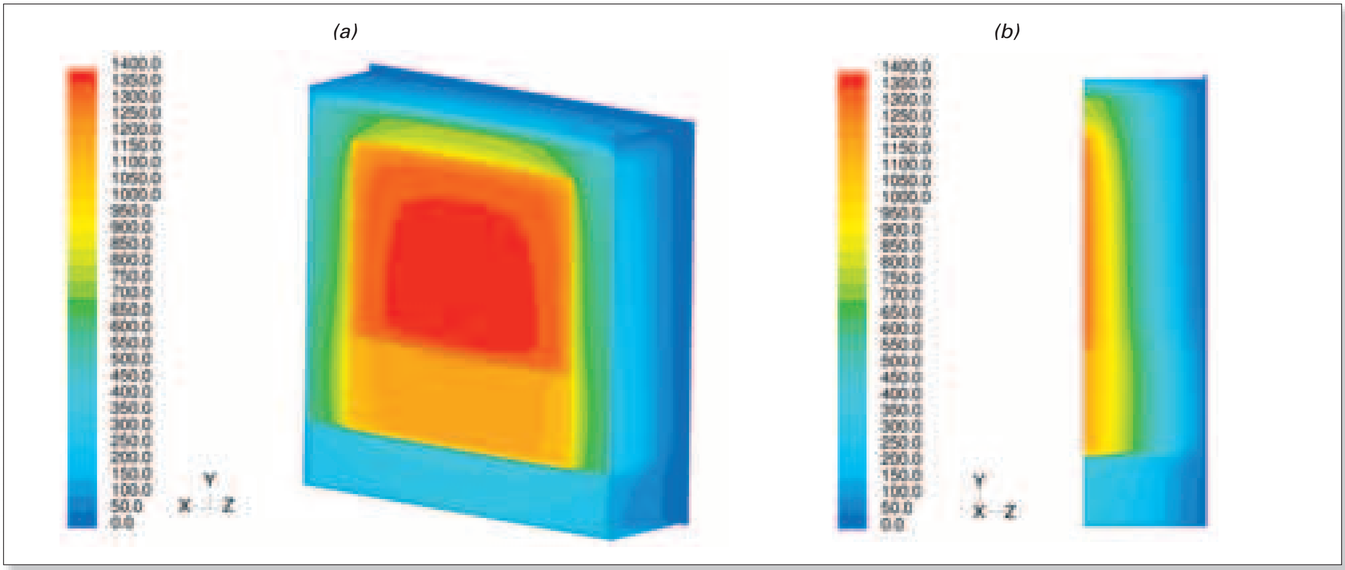

Figure 10. *Preliminary CFD modelling results of the (a) test wall hot face and (b) a cross section through the test wall.*

CFD modelling using the Fluent 6.1 software (Fluent Inc., Lebanon, USA) was used to create a three-dimensional heat distribution model through the entire wall and the results are illustrated in Figure 10. The orange and red area is the region of the test wall that was directly heated (1.2 m²). Figure 11 depicts the test wall with the attached furnace chamber as a three-dimensional schematic outline with the same spatial dimensions as the CFD modelling results and illustrates that the limited heating of the outer wall regions was due to the effective chamber insulation.

The CFD results indicated that more heat was transferred through the graphite bricks in the lower region of the test wall because of their higher heat conductivity than through the ANKER T15 bricks. Furthermore, the heat fluxes demonstrated an optimal

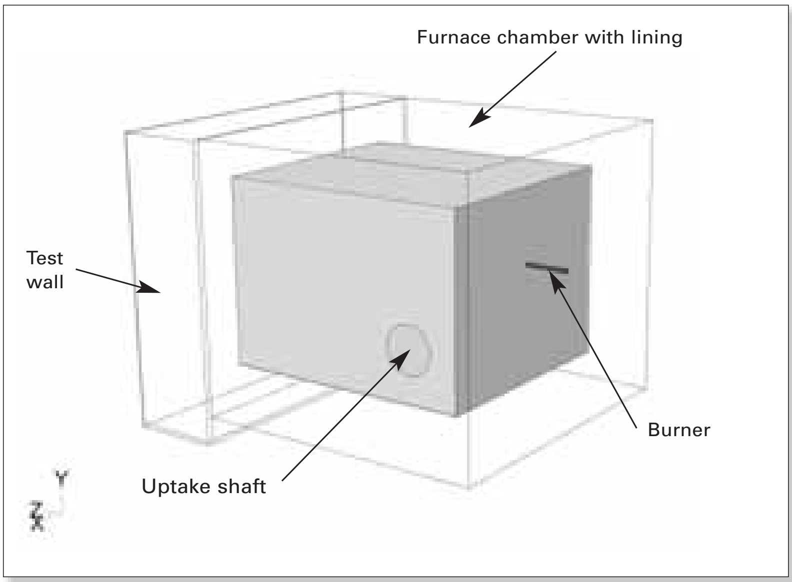

Figure 11. *FLUENT® three-dimensional schematic representation of the test wall and furnace chamber.*

contact between the ramming mix, the bricks, and the steel shell; therefore, using this design a high heat flow rate through the lining could be achieved.

Conclusion

An experimental furnace test wall was developed to provide more data for the CFD modelling under practical conditions. Furthermore, using experimentally determined values enables the modelling to be performed without using estimated values. Therefore, a more accurate temperature distribution can be calculated and a modelling capability can be established that is not only essential for developing optimal furnace linings but is also important for the ongoing refractory expansion calculations.

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