Heat Transfer Design Considerations for Refractory Linings with Steel Anchors, Part 2

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Part 1 of this paper dealt with the thermal conductivity of refractory materials and the problem of 1D heat transfer. It is concluded that the current design procedure for refractory structures using 1D heat transfer models can result in serious temperature prediction errors and the use of simplified forced convection coefficient equations can lead to errors of 25 % or more. The analysis and historical data shows that manufacturer's published thermal conductivity values can be very inaccurate for unknown reasons. The error in the manufacturer's thermal conductivity can be by as much as 50 %. Research [1, 2] has shown that correlations based on the hot-wire test can accurately predict refractory thermal conductivity. It has been found that using hot-wire thermal conductivity data with an interface air gap is an accurate method for predicting temperature profiles in refractory systems. Heat transfer analysis is a critical step in the design stage of refractory lining structures yet numerous simplifying assumptions are regularly made. This paper discusses 2D and 3D heat transfer analysis and recommends that there is a need for more accurate information to be published by manufacturers.

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1 Introduction

The heat transfer analysis of multi-layer refractory concretes in both transient and steady state conditions is particularly important for many pyro-processing industries. Knowing the temperature profile through the different layers is important for design and operational trouble-shooting. The design of refractory linings is becoming increasingly important both structurally and in energy efficiency terms. Industry "fitness for service" (FFS) guidelines for pressure vessels require that the plant is safe for personnel and the public. FFS assessments will include refractory linings and the practice of simply changing the refractory design without proper engineering approval could leave companies exposed.

Heat transfer theory is generally well understood and it is possible to predict temperature profiles under various conditions with reasonable accuracy when accurate thermal property and convective/radiative boundary conditions are known. Refractory linings are generally composed of multiple layers of varying insulating materials and a dense abrasion resistant hot face layer.

In the design of refractory structures one-dimensional (1D) steady state models are generally used. This may be adequate when selecting refractory materials but is inadequate when designing refractory structures (refractory concrete plus the anchoring system). This is due to the different temperature profile of the steel anchors. Earlier work [4] has shown that creep rupture stress is a significant when undertaking refractory structure design. Thus the design of refractory structures needs to consider all the lining components, i.e. the refractory and anchoring system.

In many cases, simplified assumptions are made when undertaking a heat transfer analysis for refractory structure design. However, given the advances in computing technology these simplified assumptions do not need to be made, as the software exists that automatically adjusts for the varying parameters. The difference between 2D and 3D analysis is discussed along with the effect of air gaps at the interface. 3D numerical analysis shows that the temperature profile adjacent to refractory anchors is not one-dimensional and the vee part of the anchor tends to act as a heat funnel.

2 2D and 3D thermal analysis

It is known that thermal conductivity of metals is significantly greater than refractory that of concretes. However, the effect of the increased heat transfer within the refractory system with metal refractory anchors has not been well studied or published.

The analysis below considers the heat transfer in a refractory structure incorporating steel anchors using 2D and 3D numerical analysis techniques [3]. This analysis shows

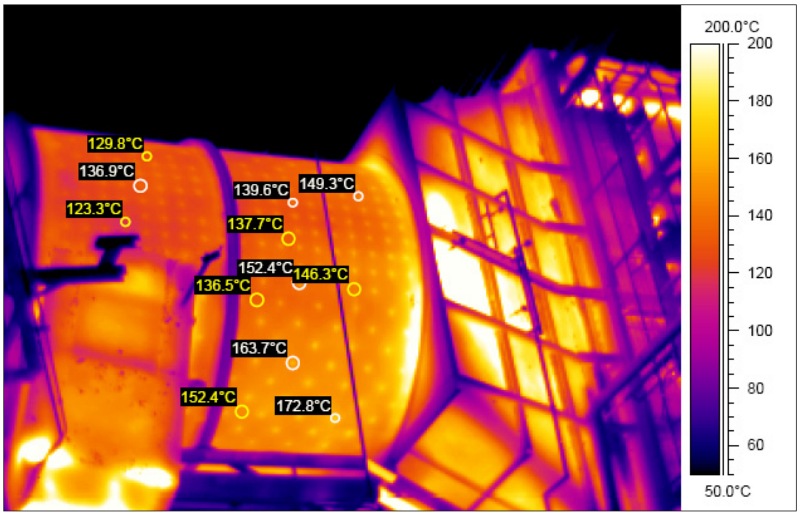

Fig. 1 Thermovision of furnace shell showing anchor base hot spots (white circles)

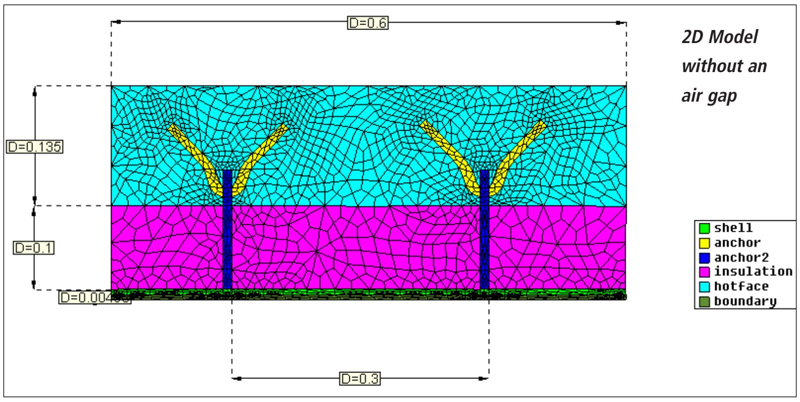

Fig. 2 Geometry for 2D thermal analysis showing anchors and refractory layers

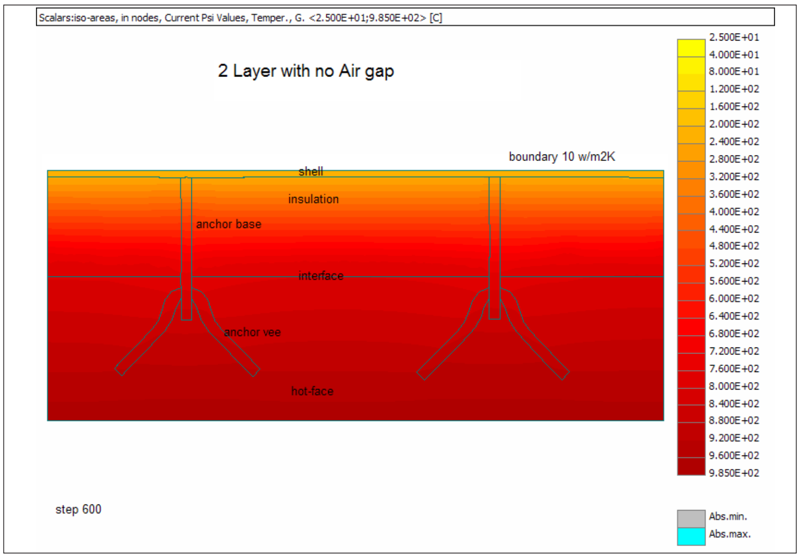

Fig. 3 2D two layer thermal model with refractory anchors showing the overall temperature profile and temperature bridging between the anchor vees

that the temperature around the anchors is not one-dimensional and as a result, 1D steady state analysis does not correctly predict shell temperatures at anchor locations. This is particularly important for design purposes. Infrared imaging of refractory lined vessels with steel anchors shows that the surface temperature where anchors are welded to the shell has an elevated temperature, typically in the order of 6 °C to 10 °C. Fig. 1 is an infrared image of a furnace with a two-component lining (insulation and hotface) of approximately 230 mm thickness. This shows the small hotspots where the anchors are located.

Thus the temperature profile around the refractory anchors is not one-dimensional and 1D steady state analysis cannot be used to predict shell temperatures at anchor locations. However, knowing the temperature profile in refractory anchors is particularly important for design purposes.

2.1 2D thermal analysis

A 2D thermal analysis was carried out on an anchored refractory structure using ATENA [3] to study the temperature around the anchors assuming perfect conduction. The model is composed of three layers, hot-face 135 mm thick with thermal conductivity of 1,6 W/m · K, an insulation layer of 100 mm with thermal conductivity of 0,3 W/ m · K and steel anchor base (10 mm x 20 mm) with thermal conductivity of 20 W/ m · K. The shell boundary layer had a convective coefficient of 10 W/m^2 · K. The hot-face temperature was set at 985 °C. The model mesh is shown in Fig. 2. The overall temperature profile is shown in Fig. 3.

Fig. 4 shows the 2D temperature profile around the anchor in the hot-face and the insulation/shell with perfect conduction and no air gap at the interface.

The 2D analysis shows that the temperature between the vee can increase by approximately 10 °C under ideal conditions. However, the 3D analysis shows that the anchor vee does not have sufficient mass around the anchor vee for temperature bridging to occur.

However, if sufficient anchors are in place and in close proximity to each other then temperature bridging is likely to occur. The temperature in the insulation layer for this case remains reasonably linear. At the shell there is a zone immediately below the anchor base, which is hotter than the surrounding shell. This is due to the higher thermal conductivity of the anchor material.

The analysis does show that refractory anchors are high thermal conductors (compared to refractory) and the temperature immediately below the anchor will be hotter than the surrounding refractory.

While a 1D analysis is insufficient to capture the variation in temperature profile in the presence of refractory anchors, a 2D thermal analysis clearly shows that the temperature of the refractory anchor will be higher at the shell due to the anchor's thermal conductivity. It is possible that the temperature of the refractory anchor at the interface will be lower than the refractory. The temperature profile described above is one case only and the final temperature will depend on the material thermal conductivity, insulation and hot-face material thickness, anchor material and thickness and the shell boundary conditions.

2.2 2D Thermal analysis with an air gap

Due to the fact that an air gap will exist between the refractory layers after firing the thermal analysis was also carried out for the same two-layer system but with an air gap at the interface. The model is shown in Fig. 5. The model has the same dimensions and boundary convection coefficient as that shown in Fig. 2.

Fig. 6 shows the 2D temperature profile through the centre of the anchor for the model with an air gap. The results show shell temperature immediately below the anchor base is approximately 202 °C. Moving away from the anchor base the shell temperature reduces to approximately 181 °C. Without an interface air gap the shell temperature below the anchor base has been predicted at 238 °C and 233 °C away from the anchor base. A comparison is shown in Fig. 7.

The 2D thermal analysis shows that an air gap in a two-layer refractory system will reduce the temperature at the interface and the anchor base but the hot zone area at the anchor base will be more pronounced. Fig. 7 is an overlay of the anchor base and shell showing hot area. The estimated diameter of the hot zone under perfect conduction (without an air gap) conditions is approximately 60 mm. It can be seen that the elevated temperature zone (diameter) of the shell is approximately twice that when there is no air gap at the interface.

It has been shown that the temperature profile around a refractory anchor is significantly different to a 1D thermal model. The analysis shows that anchors act as a thermal

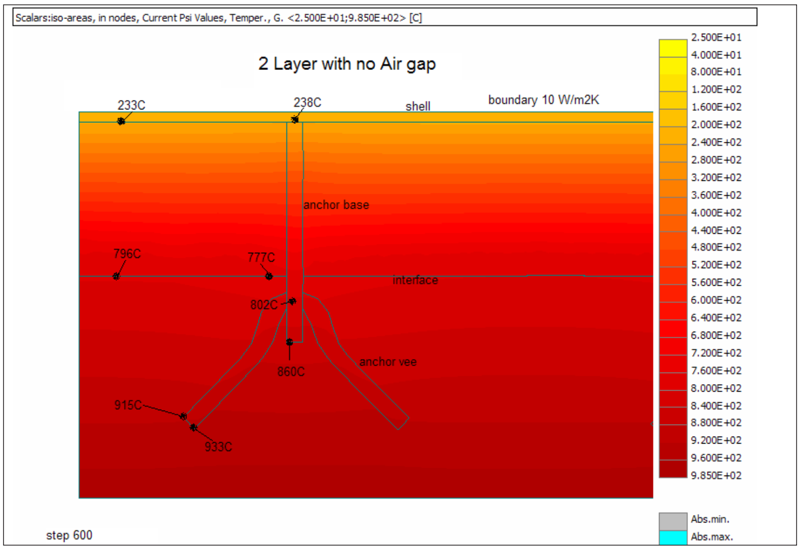

Fig. 4 2D heat transfer analysis showing the temperature profile around the anchor (no air gap at interface)

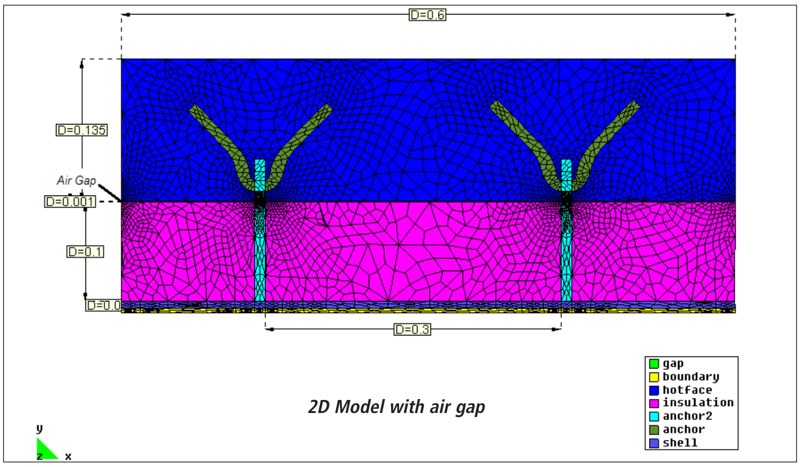

Fig. 5 2D two layer concrete model with an air gap

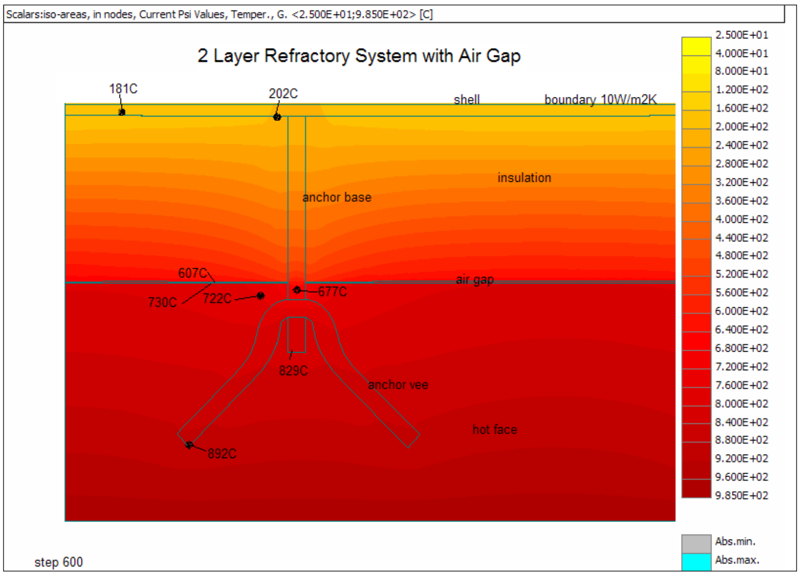

Fig. 6 2D thermal model (1/2 section) with an air gap at the interface between the concrete layers, shell boundary convection of 20 W/m² · K

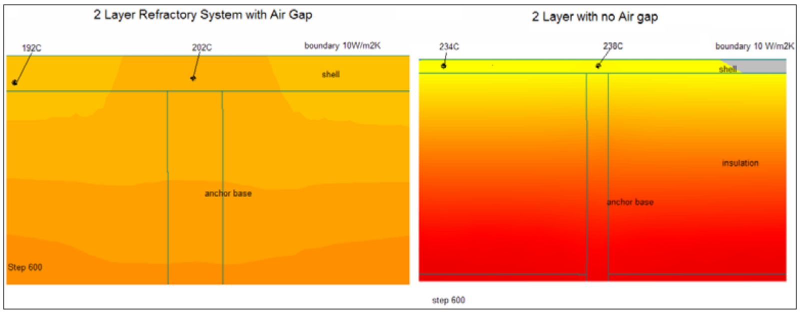

Fig. 7 Overlay of anchor base and shell hot zones showing increased temperature area

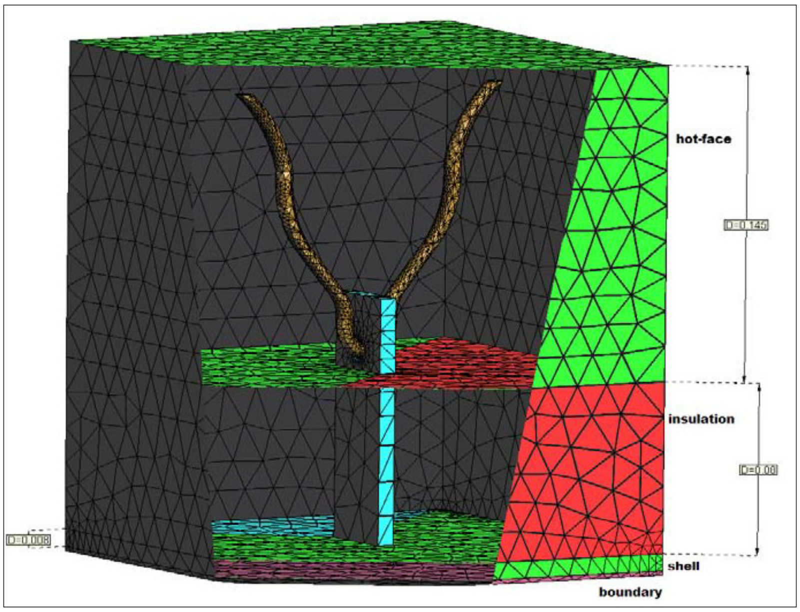

Fig. 8 3D model of a two layer refractory system with cut-out showing anchor profile

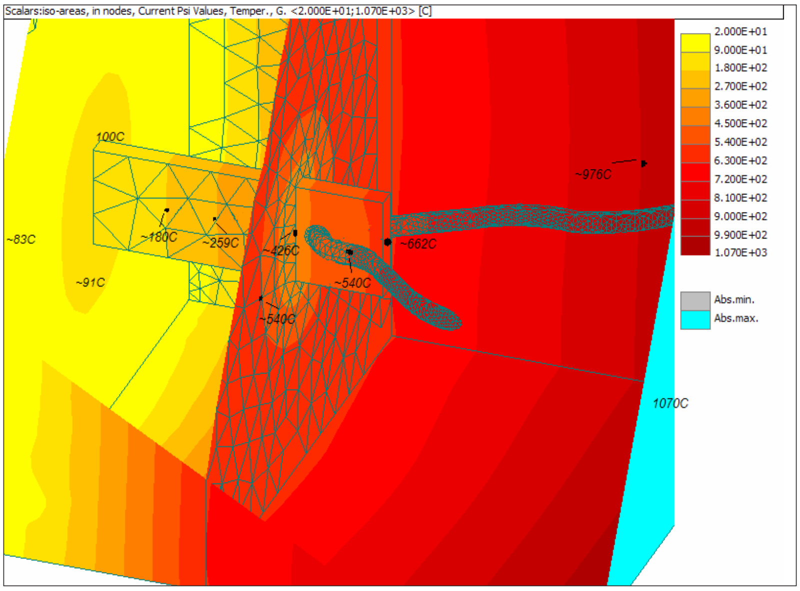

Fig. 9 3D temperature profile for a two layer system with high convection the shell (100W/m² · K)

conductor and can increase the temperature at the shell at that location by up to 10 °C.

Field results show the temperature increase is approximately 10 °C above the surrounding temperature. The results show that caution must be exercised when using 2D analysis as temperature bridging can occur around an anchor, which will not happen in a 3D model. However, it does indicate that if anchors are very closely packed then temperature "bridging" could occur which will result in higher temperatures between anchors near the interface zone.

3 3D thermal analysis

A 3D thermal analysis was carried out using ATENA [3] under perfect thermal conduction conditions to show the temperature profile around the anchor. The 3D model is of a two-layer system (insulation and hot-face) with a hot-face thickness of 146 mm and insulation of 80 mm with a two-part type anchor (Fig. 8). The temperature boundary conditions were a shell boundary convection of 100 W/m² · K and 1110 °C surface temperature at the hot-face.

The temperature profile is shown in Figs. 9 – 13. The 3D analysis shows that refractory anchors facilitate in conducting heat to the shell and the temperature in the refractory surrounding the anchor can also be lowered. The extent of cooling around an anchor is very dependent on the quality of refractory (honeycombing) and the cross-sectional area of the anchor.

However, it is very important to be aware that the quality of the welding of the anchor to the shell and shadowing (poorly consolidated concrete) around the anchor at the interface will significantly affect the temperature profile and consequently the creep rupture stress.

This analysis shows that the temperature around the anchor and refractory can vary depending on materials, anchor type and boundary conditions. Under perfect conditions the anchor interface temperature can be lower by approximately 100 °C.

Fig. 10 shows the temperature along a steel anchor embedded in a two-layer refractory concrete system. This shows the temperature around the anchor is decreased when embedded in the hot-face and increases at the shell.

The analysis shows that the temperature decrease is confined to the volume around the anchor.

The analysis also shows that anchors with large cross-sectional areas that penetrate into the hot-face will conduct heat at a faster rate than the surrounding refractory. Thus the temperature will be higher at the shell and lower at the interface zone.

4 Conclusions

It is concluded that the current design procedure of using a 1D heat transfer model is insufficient to predict temperature profiles in refractory systems comprising refractory anchors.

In the field it is regularly observed that two-layer refractory systems have air gaps between refractory concrete composite layers. The thermal analysis in Part 1 of this paper shows that a gap in the order 1–2 mm at the interface between the concrete layers can be significant and should be taken into consideration. However, if the manufacturer's datasheet value for thermal conductivity is used with air gaps then the shell temperature will be underestimated (i.e. the shell temperature will be lower than actual). The thermal analysis should be carried out using an air gap and the thermal conductivity calculated from the hot-wire method.

The 2D analysis shows that the temperature between the vee can increase by approximately 10 °C under ideal conditions. However, the 3D analysis shows that the anchor vee does not have sufficient mass around the anchor vee for temperature bridging to occur. However, if sufficient anchors are in place and in close proximity to each other then temperature bridging is likely to occur.

A 3D thermal analysis shows the temperature around the refractory anchor will be higher at the shell due to the anchor's thermal conductivity. This analysis has found that under perfect conduction then the temperature around the refractory anchor does not follow the temperature profile predicted using 1D heat transfer models.

Our analysis shows that 1D or 3D thermal analysis, which includes air gaps between layers, should be used when designing refractory structures. It has also been shown that 1D analysis will only predict the temperature profile through the refractory away from the anchors.

A 3D thermal analysis shows temperature "bridging" does not occur between an anchor vee as predicted by 2D analysis. However, it does indicate that if anchors are very closely packed then temperature "bridging" may occur which will result in higher temperatures in the anchor around the interface zone. It is recommended that 3D thermal analysis be carried out when designing refractory structures. This is particularly important as the shape of the anchor can affect the temperature, which in turn can significantly decrease the creep rupture stress. If 1D analysis is used that the limitations of the results must be clearly explained.

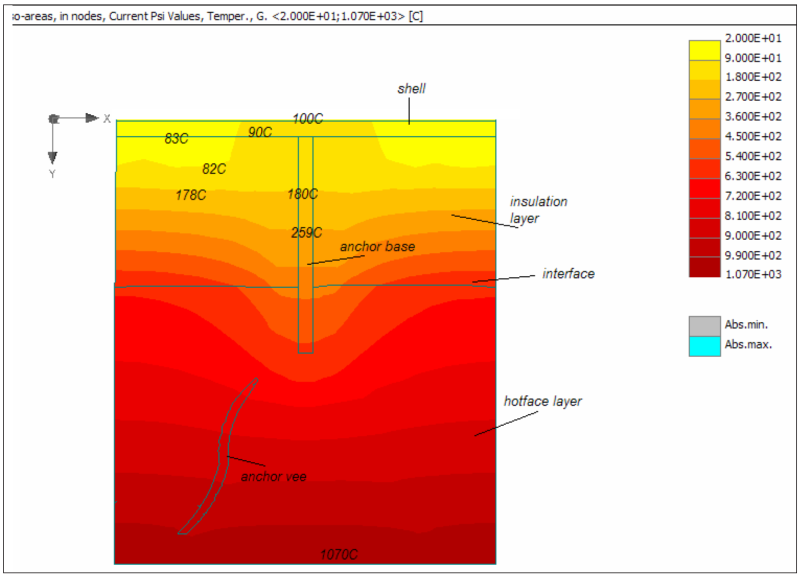

Fig. 10 Elevation view showing the temperature profile near the centre of the anchor

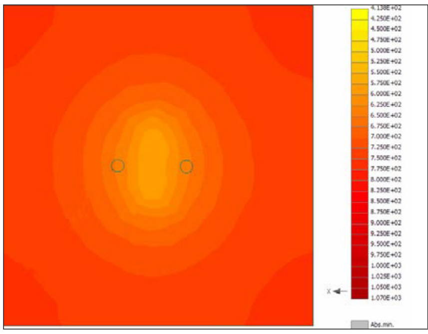

Fig. 11 Section (X-Z) at 0,13 m from the anchor base

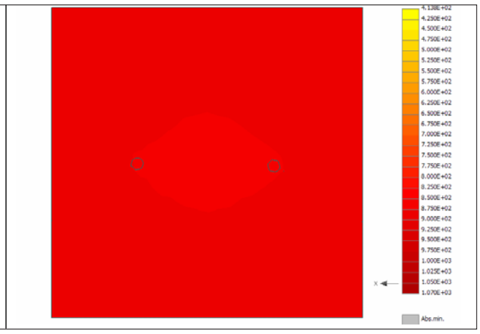

Fig. 12 Section (X-Z) at 0,83 m from the anchor base

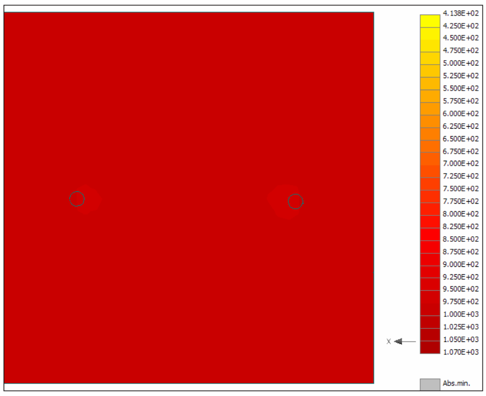

Fig. 13 Section (X-Z) at 0,21 m from the anchor base

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Remark from the editor: Part 1 has been published in refractories WORLDFORUM 2 (2010) [2] 94