Computer-Aided Thermo-Mechanical Stress Modelling of Different Rotary Kiln Outlet Designs

Introduction

The outlet section of the cement rotary kiln is routinely subject to very severe operating conditions. This results in thermo-mechanical stresses caused by the lining thrust and the kiln shell conditions (e.g., retaining elements and ovality) and thermal load (e.g., overheating and thermal shocks). Furthermore, whilst the lining thrust is principally initiated by thermal expansion of the lining, it is also caused by the lining weight and the number of kiln revolutions (up to 5 rev/min). The resulting problems that include deformation of the outlet segments and retaining rings, as well as premature lining wear are well established (Figure 1).

Therefore, to investigate the progression of the thermo-mechanical stresses caused by lining thrust this particular area was investigated using a two-dimensional computer-aided calculation model.

Various outlet designs have been developed by different engineering companies for this highly thermo-mechanically stressed region, including single and double retaining rings, the conical outlet design, conical outlet segments, and the innovative Veitscher-Magotteaux retaining ring system.

In the following sections three representative designs—double retaining rings (height 70 mm), the conical outlet design, and the Veitscher-Magotteaux retaining ring system (Figure 2) will be compared using two-dimensional axisymmetric finite element models. Whilst the entire kiln was modelled during the analyses, the results will only focus on the outlet section.

Modelling

The Finite Element Method (FEM) program Diana, Version 8.1 (TNO, Delft, The Netherlands) was used to create two-dimensional axisymmetric models of the different outlet designs, excluding the influence of the radial joints in the brick lining.

To accurately represent the kiln it was divided into the individual bricks, mortar, and expansion joints (comprised of attached cardboard and ceramic felts). The specific expansion allowances are detailed in Figures 3, 4, and 5.

It is well established that the thermal expansion of basic bricks is much greater than that of alumina bricks (Figure 6). Therefore, basic bricks are delivered with 2 mm thick cardboard attached. In the model, different expansion allowances were modelled using interface elements. The distances between the bricks are detailed in Figures 3, 4, and 5. The 2 mm spaces were representative of the cardboard, the 7 mm and 5 mm spaces were expansion joints, and the 0.3 mm spaces were either the modelled space during subsequent heat ups after the cardboard had burnt out or the mortar joints in the original lining design, assuming a 30% compressibility. Movement between the lining and the kiln shell was modelled with a further interface element type that had an initial space of zero and is depicted by a red line in Figures 3, 4, and 5.
Figure 3. Expansion allowances (mm) for the double retaining ring design (a) before the initial heat up and (b) before subsequent heat ups.

Figure 4. Expansion allowances (mm) for the conical outlet design (a) before the initial heat up and (b) before subsequent heat ups.

Figure 5. Expansion allowances (mm) for the Veitscher-Magotteaux retaining ring system (a) before the initial heat up and (b) before subsequent heat ups.

Figure 6. Thermal expansion of magnesia (ANKRAL) and alumina (MAXIAL) bricks.

Figure 7. Expansion joint modelling for 2 mm cardboard spaces.
The interface elements did not transfer tensile stresses, shearing stresses, and compression stresses; however, when the space was reduced to zero, compression stresses were transferred. Using the finite element method, the behaviour of the expansion joints was modelled using a nonlinear constitutive law for the interface elements. Figure 7 illustrates this nonlinear correlation between the relative displacement and the traction transferred between the bricks using the 2 mm cardboard spaces as an example.

The brick properties used in the modelling (bulk density, thermal expansion, thermal conductivity, modulus of elasticity, and specific heat capacity) were taken from the RHI Refractories’ material specifications. In the first modelling step, the inside temperatures listed in Table II were used for a thermal analysis of the kiln. Assuming a convection coefficient of 40 W/Km², a maximum kiln shell temperature of 340 °C was calculated for the sintering zone. The thermal expansion of the kiln shell and lining was calculated using the temperature distribution determined in this first step.

### Lining Design

The following kiln data and materials (Table I and II) were used to model the entire kiln.

| Kiln diameter | 4600 mm |
| Kiln length | 63.6 m |
| Lining thickness | 220 mm |

#### Table I. Kiln dimensions.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Length</th>
<th>Material</th>
<th>Inside temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet and calcining zone</td>
<td>11200 mm</td>
<td>MAXIAL 310</td>
<td>800 °C</td>
</tr>
<tr>
<td>Safety zone</td>
<td>12000 mm</td>
<td>RESISTAL B50Z</td>
<td>800-1100 °C</td>
</tr>
<tr>
<td>Upper transition zone</td>
<td>13000 mm</td>
<td>ANKRAL R2</td>
<td>1100-1450 °C</td>
</tr>
<tr>
<td>Sintering zone</td>
<td>20200 mm</td>
<td>ANKRAL ZE</td>
<td>1450 °C</td>
</tr>
<tr>
<td>Lower transition/Outlet zone</td>
<td>7200 mm</td>
<td>ANKRAL R2</td>
<td>1450-1300 °C</td>
</tr>
</tbody>
</table>

#### Table II. Kiln zone lengths, lining materials, and inside temperatures.

Due to the expanded brick shape, where expansion had reduced the joint opening to zero, transfer of the lining thrust and the highest stress was limited to approximately one-third of the brick height (73 mm) [1].

When the entire kiln was modelled at the service temperature for the first heat up and the three outlet designs were examined (Figures 9a, 10a, and 11a) the compression stress zones, illustrated in blue, were limited to the hot face. Furthermore, the calculated maximum pressure of 50 N/mm² to 70 N/mm² was within the crushing strength limits of the brick specifications and there was no over-stress visible at the position of the retaining elements. Therefore, the positions and dimensions of the expansion joints were appropriately designed to compensate for the thermal expansion and to assure a tight lining.

However, a completely different situation is evident after a kiln is shut down and the lining is reheated. The expansion allowance initially provided by the cardboard is lost due to the downhill movement of the lining, irreversible brick expansion, and filling of open joints with clinker dust. Furthermore, the expansion joints are compacted and only provide a limited displacement allowance. The modelling results of this situation are illustrated in Figures 3b, 4b, and 5b. In the following section, the FEM modelling of the lin-

#### Modelling Results

The modelled brick deformation caused by thermal expansion at service temperatures was dependent on the distance from the hot face, the brick specifications, and the resulting temperature gradient through the brick (Figure 8).
ing operating at service temperatures for subsequent heat ups will be discussed in further detail for the three kiln outlet designs.

**Double Retaining Rings**

In the case of the double retaining ring design (Figure 9b), the uphill lining in front of the first retaining ring showed a high load at the brick hot face and excessive stress on the first retaining ring (> 100 N/mm²). Only 70 mm of the brick height was supported by the retaining rings; therefore, extreme sheering forces would occur. Furthermore, the specific load would easily exceed the strength and structural flexibility of the bricks resulting in lining failure.

**Conical Outlet Design**

The conical outlet design (Figure 10b) shows a high load over the entire lining and excessive stress (> 100 N/mm²) at the outlet segments was visible. However, due to the conical design, the load was distributed to a high number of brick rings and the axial thrust was partially transformed into radial forces. Under these conditions the bricks are more capable of withstanding a certain level of lining thrust. These results indicate that to avoid excessive loads on the outlet segments, particular attention should be focused on the expansion joint dimensions.

**Veitscher-Magotteaux Retaining Ring System**

Expanding on the basic concept of the conical outlet design, a multistep conical retaining ring system was developed in 1992 by Veitscher Magnesitwerke (RHI Refractories, Vienna, Austria) in cooperation with Magotteaux (Vaux-sous-Chèvremont, Belgium). This outlet design was termed the Veitscher-Magotteaux retaining ring system.

During reheating of the Veitscher-Magotteaux retaining ring system (Figure 11b) there was also a high load over the entire lining in front of the retaining elements; however, this load was continuously dissipated within the conical steps. This dissipation was not only due to diverting the axial thrust into radial forces but the situation was also considerably improved because the load was distributed onto three of the brick faces (sloped and side faces). This
resulted in the discharge end of kiln displaying a homogeneous force distribution and an acceptable load at the outlet segments.

**Stress Centres**

In addition to the investigations described in this paper, further calculations were performed to identify the most critical area of the different outlet systems. Thereby, the retaining elements were exposed to an extreme axial force (Figure 12) caused by an excessive lining displacement. As expected, the highest load occurred directly at the retaining elements and is denoted by the dark blue areas (see Figure 12). In summary, a maximum pressure of 120 N/mm² was calculated for the Veitscher-Magotteaux system, whilst the maximum pressure of the conical outlet was 144 N/mm², and the retaining ring was 260 N/mm². Whilst the absolute values should not be considered, the relationship between the three maximum pressures provides a clear indication of the variation in the different loads on these systems.

**Conclusion**

It is important to emphasize that all the discussed outlet designs have been shown to operate successfully under normal conditions when the lining is accurately installed. However, currently these normal operating conditions are rarely found and the axial thrust is frequently compounded by additional stresses, including deformation of the kiln shell, relative lining movement, overheating, and thermoshock. Furthermore, due to chemo-thermal stresses (e.g., clinker melt infiltration, salt deposits, and redox phenomena) the strength and structural flexibility of bricks is considerably affected. Under such serious operating conditions only the most advanced outlet design—the Veitscher-Magotteaux retaining ring system—is able to provide satisfactory performance.

**References**


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