Improving flue gas tunnel reliability

J. Quintilliani and **W. Russell** of Blasch Precision Ceramics discuss how the reliability of primary reformer flue gas tunnels can be improved through the application of engineering design and improved material selection.

Steam Methane Reforming is one of the most prevalent routes for the conversion of methane (CH_4) to petrochemicals. The process produces a mixture of hydrogen and carbon monoxide referred to as "Synthesis Gas" or "Syngas". In the most common configuration, methane is put through a primary reformer which is essentially a large refractory lined furnace with centrifugally cast chrome-nickel tubes mounted vertically in the furnace. The process gas and steam are fed downward over a catalyst which is heated by burners mounted in the side or top of the furnace. Along the bottom of this unit are refractory tunnels that function to distribute exhaust discharge uniformly from the furnace, optimizing process efficiency and tube reliability. These tunnels have always suffered from reliability issues which can lead to unexpected shut downs, losses in efficiency, or at the very least high turnaround costs.

Existing Designs

The current design and construction of flue gas tunnels in Steam Methane Reformers is relatively simple. The sidewalls are typically constructed directly against the furnace shell floor starting with insulating firebrick then transitioning to regular firebrick configured with either a flat face or tongue and groove. The bricks are all secured with refractory mortar. As the walls are constructed, half blocks are left out in regular patterns to provide holes to allow gas passage from the furnace through the wall into the tunnel. Once the walls of the tunnel have been constructed, the tunnel covers are placed on top. These lids, often called coffin covers, are often made from large slabs of refractory. In order to account for thermal expansion, large expansion gaps are created at regular intervals. This expansion gap is a critical feature, necessary to accommodate for anticipated thermal growth. In order to support these tunnel walls, intermediate support structures, or pilasters, are often integrated into the outer walls of tunnels in an effort to prevent the walls from leaning and collapsing.

Failure due to thermal stress

One of the prevalent tunnel failure modes seen in the field is the collapsing of the lids. Once installed, the lids are viewed to act as a simply supported beam. The belief is that a crack in the middle of the lid is the result of the ratio between the span and the material thickness. However, calculations indicate that the static load alone imparts very little stress on the lids, and will not likely result in a failure. Figure 1 is a finite element analysis (FEA) of a typical extruded lid installed on a tunnel at a constant service temperature of 1900°F. The lid has no external forces acting upon it other than its own weight, which resulted in a maximum stress of just 10psi; well below the hot modulus of rupture (HMOR) of typical refractories. In order to find the source of these failures, it is necessary to also consider thermal stress. Thermal stress is generated by temperature gradients within a body resulting in strains associated with differential thermal expansion. These strains drive a corresponding stress proportional to the modulus of elasticity of the material. Failure results when the thermal expansion from one area of a component is different than another area. Failure occurs when the resulting stress exceeds the rupture strength of the refractory. If the temperature in the convection section of the furnace is different than the temperature inside the tunnels, even for a short period of time, the potential for thermal stress is present. Figure 2 shows an FEA of the same lid used in Figure 1, installed on a tunnel with the temperature on the top surface of the lid at 1910°F and the temperature on the bottom surface of the lid at 1900°F. The lid has no external forces acting upon it other than its own weight. A differential temperature of 10 degrees across the lid results in a max stress of 1500psi, above the HMOR of many refractory materials. In a particular instance where a very large number of the lids of a tunnel failed during the same campaign without any of the

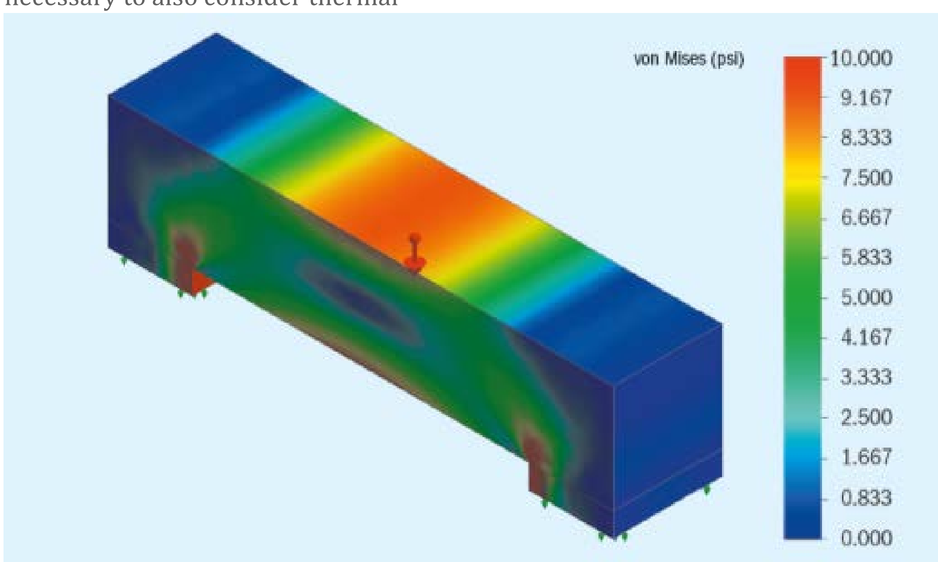

Figure 1: FEA of tunnel lid at constant 1,900°F

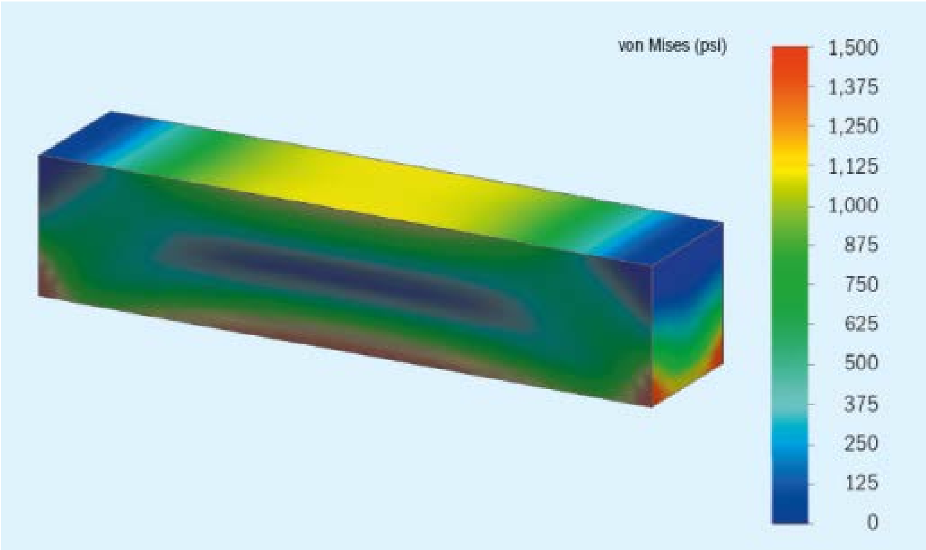

Figure 2: FEA of tunnel lid at variable temperature between 1,900°F and 1,910°F

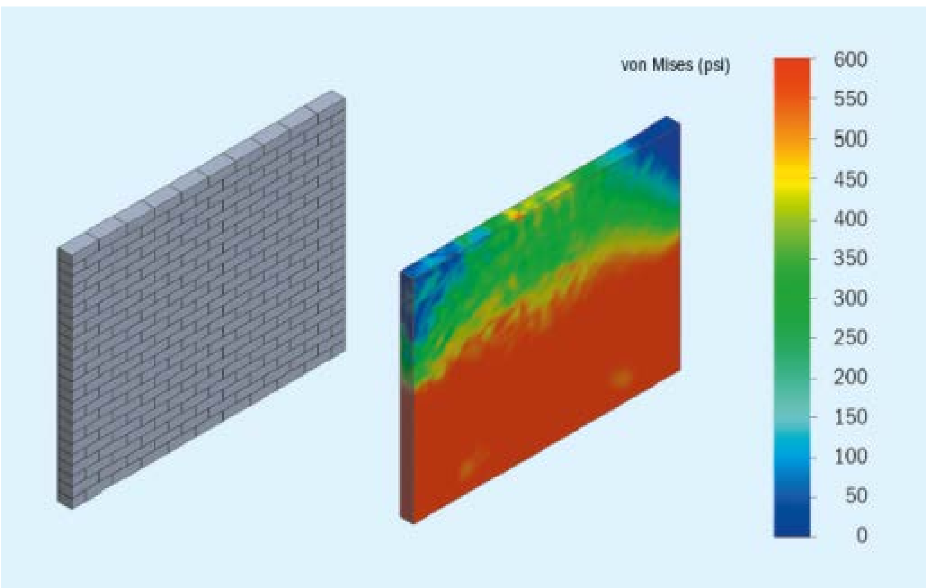

Figure 3: FEA of a fully mortared 10' tunnel wall section with variable temperature

walls collapsing, the mode of failure was most likely thermal stress.

Decreasing the lid thickness will lower the thermal mass and increase the bulk conductivity resulting in reduced thermal gradients and lower resultant associated stresses. In general, the wall thickness should be as thin as possible without sacrificing the overall stability of the tunnel.

Failure due to material selection

Another important factor in the performance of the tunnel lids is the material selected for construction. There are several properties to consider when selecting a material including HMOR and creep resistance. Creep occurs when a material slowly but permanently deforms under long-term exposure to high levels of stress that are still below the material rupture strength. Creep of a lid will result in a "sagging" of the center span and will change the interaction force between the lid and the tunnel walls, and eventually lead to a failure. The result on the tunnel walls is a transmission of the lid's mass at an angle that is a few degrees off of the vertical axis and will encourage the walls to separate further apart at the top than at the bottom. This phenomenon is not limited to tunnel lids; the base of the tunnel is also subject to this type of time dependent deformation. Conventional tunnel construction uses hundreds of thousands of pounds of refractory brick and lids. All of this mass rests on a final base layer of insulating fire brick. A conventional tunnel cross section with a solid lid will result in a load on the supporting IFB layer of over 10psi. Published data using ASTM testing suggests that at the temperatures present in the reformer furnaces the IFB layer will deform a full 1% under those loads in 100 hours. The deformations of the IFB layer can prematurely compress the fiber allowances for thermal expansion, reduce the overall insulating value of the IFB, and impact the stability of the foundation of the tunnel walls, either of which can result in failure. The effects of temperature and tunnel mass are not limited to the internals of the furnace, but can also cause deformation of the supporting steel furnace structure, leading to a non-uniform furnace floor.

Proper material selection should include confirmation that the modulus of rupture at the service and excursion temperatures of the furnace has a sufficient factor of safety when compared to the associated static load stresses. Also, any material being selected for use in the reformer furnace should have the highest resistance to creep reasonably available, as a reduced creep will prolong the life of the tunnel system and prevent premature failures. Finally, reducing the component wall thickness will reduce the overall weight of the tunnel which greatly decreases the PSI load on the IFB base. A 60% reduction in weight will translate to an order of magnitude less load on the IFB layer. The design of the tunnel could also incorporate a "base" component that spreads the weight of the tunnel over up to five times the area of conventional designs.

Failure due to thermal expansion

Differential thermal expansion can occur not only in situations with different design materials, but also across large sections of materials that are expected to act as a single body. A conventional tunnel design will use fiber expansion joints roughly every 6-10 feet of wall length, with all of the building components in between adhered to one another with a refractory mortar causing the wall sections to behave as a single body. Figure 3 shows an FEA performed to

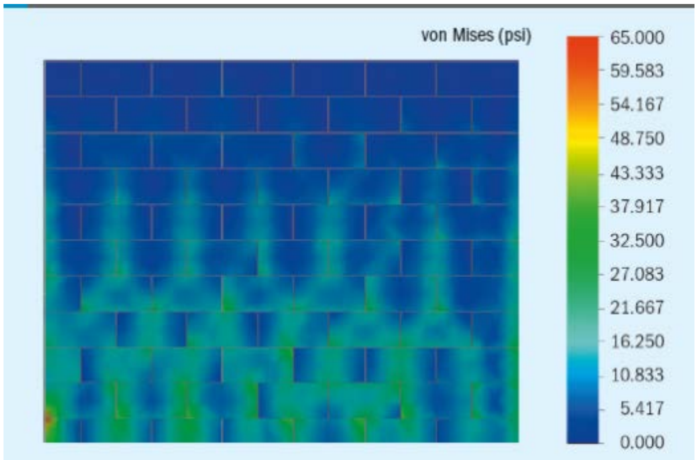

Figure 4: FEA of a non-mortared 10; tunnel wall section with variable temperature

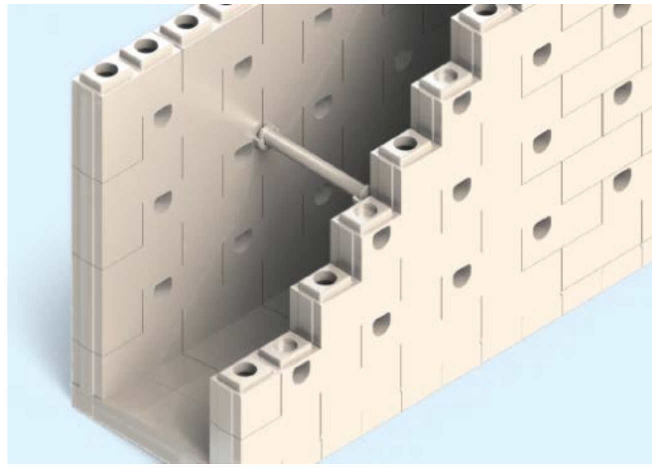

Figure 5: Cross beam support for tunnel system

determine stress levels associated with a differential temperature from the top of a fully mortared 10' wall section to the bottom. The fully mortared wall section was treated as a single body for the purposes of the analysis. The wall section has a uniform temperature distribution with 1925°F at the bottom and 1900°F at the top. The FEA also included a simulated weight of the tunnel lids and gravity, but no other external forces. This analysis showed that the stress of this system exceeds the 500psi HMOR typical of a standard refractory mortar. Since the mortar joints are the weakest point on the wall, they will crack to alleviate the stress, often resulting in overall wall stability issues. Figure 4 shows an FEA performed to determine stress levels associated with a 10' wall section comprised of 18" W x 9" T blocks that have individual expansion gaps. The conditions and external forces for this analysis are identical to that of the mortared wall section. The result is a system with a peak stress of less than 65psi.

Properly accommodating for thermal expansion is one of the most difficult aspects of any thermal application design. A conventional tunnel design has a different material, conditions and design for the tunnel lid and the tunnel base. Often tunnels are designed with low density refractory or fiber insulation in the "base" area in between the wall supporting IFB columns. By design, the tunnel base area is cooler than the lid. The tunnel lid can expand as much as 3/8" pushing the tunnel walls apart with it, whereas the fiber insulation imparts far less expansion on the tunnel walls. The resulting trapezoidal tunnel cross section is far more susceptible to buckling and ultimate collapse.

In certain situations tunnels have been found at the conclusion of a furnace campaign to have alternative movement in the lateral direction. This is known more commonly as "snaking" and is the result of the overall length of the tunnel attempting to expand to a greater extent than that allowed by the expansion joints. Snaking can crack the mortar, separate walls from lids, and push the walls off of the IFB base; all of which can lead to failure. Proper material selection and installation procedures are important to prevent "snaking". Many materials will increase in overall dimension when re-heated, increasing variability and adding challenge to the thermal expansion management. Because the coefficient of thermal expansion for refractory components is nonlinear, it must be fully characterized and understood to ensure that proper expansion joints are created.

In order to best accommodate thermal growth, every block should manage its own thermal expansion and the entire system must be mortar free, but for stability reasons must be completely interconnected. Proper thermal expansion management also suggests a tunnel system should utilize a "base" component that has the same material and similar dimensions to the "lid" component. This will ensure that the tunnel expands and contracts equally on both the top and bottom of the wall. Cross beam supports can be added into the system at predetermined locations to arrest buckling if it does begin (Figure 5). Buckling can also be arrested with a tight tolerance mating feature in the wall components, such that the rotation of a block in relation to the block below it results in direct contact. This resulting tunnel system now requires a sufficient amount of stress to break the block wall (Figure 6).

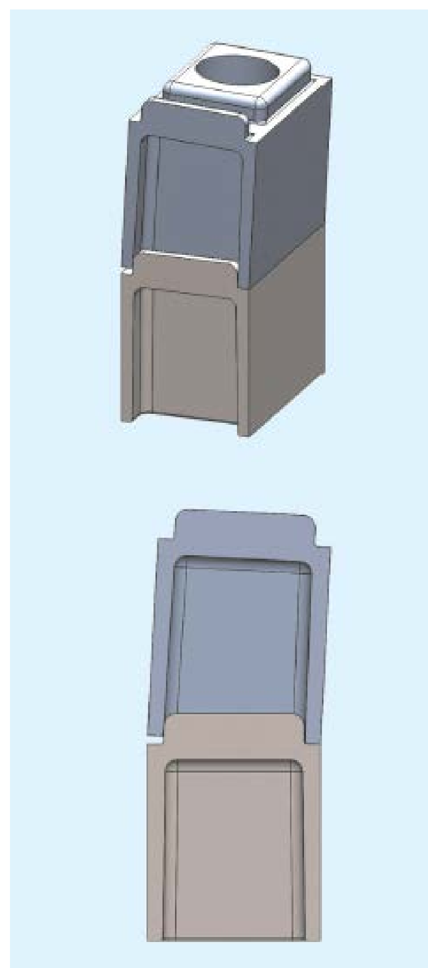

Figure 6: Tight tolerance engaging mating features