A Simplified Approach to the Contact in Thermo-mechanical Analysis of Refractory Linings

Y. Kaymak*,[1]
[1]VDEh-Betriebsforschungsinstitut GmbH
* Sohnstr. 65, 40237 Düsseldorf/Germany, yalcin.kaymak@bfi.de

Abstract: The geometrical design and material choice for a refractory lining requires a complete understanding of its thermo-mechanical behavior. Design engineers clearly need a tool for fast and efficient computation of thermo-mechanical state of refractory linings under various conditions. However, standard simulation models and their solutions suffer as the linings are composed of many refractory blocks in contact. Therefore, a simplified approach to the contact in thermo-mechanical analysis of refractory linings and its implementation are introduced. This method provides a much faster model preparation and solution than the traditional contact models with an excellent accuracy. The introduced technique is suitable to a wide range of industrial refractory linings such as blast furnaces, converters, ladles, etc.

Keywords: Heat Transfer, contact, refractory linings, thermal stresses.

1. Introduction

The geometrical design and material choice for refractory lining of large scale industrial furnaces requires a complete understanding of its thermo-mechanical behavior. Design engineers clearly need a tool for fast and efficient computation of thermo-mechanical state of refractory linings under various conditions. However, standard simulation models and their solutions suffer as the linings are composed of many refractory blocks in contact, which is practically impossible to model with today's standard computers. Therefore, a simplified approach to the contact modeling in thermo-mechanical analysis of refractory linings and its implementation are introduced in this work.

2. Methods

The knowledge of the temperature field is essential for the thermal design of the refractory lining and luckily with the help of simplifying assumptions most of the time it is easy to establish the worthy heat transfer models. The thermal boundary conditions in standard heat transfer models are usually expressed in terms of convective and radiation type of boundary conditions. If there are discontinuities through the heat flow direction due to refractory block interfaces, they should be included in the model in terms of thermal resistive layers.

The knowledge of stress/displacement field is also as important as the knowledge of the temperature field in order to understand the thermo-mechanical behavior of the refractory lining walls. Only after a full understanding of thermo-mechanical behavior, engineers can develop strategies to control the formation of cracks/gaps due to inconvenient distribution of the thermo-mechanical stresses over the refractory blocks. The modeling of the thermal stresses in an assembly of hundreds/thousands of lining blocks is quite challenging as the contact interaction of individual refractory blocks complicates and enlarges the models. Such complicated models can be solved only using super computers which are usually not an available tool for ordinary design engineers. Therefore, a simplified approach to the contact in thermo-mechanical analysis of refractory linings needed to be developed. Thanks to the ordered regular structures of the refractory blocks in the lining walls, the contact stress patterns are not that complex. The contact interfaces between the blocks let the transfer of compressive stresses but not tensile stresses. Also thanks to COMSOL, as it lets us to control the field equations at low level so that the tensile stresses between blocks can be eliminated.

This approach basically uses the principle shown in Figure 1. The refractory blocks can sustain compressive stress but cannot sustain tensile stresses. By adaptively changing the initial stress state in tensile regions in certain directions depending on the placement and alignment of refractory blocks in the lining, the effect of refractory separations and contacts can effectively be simulated globally via COMSOL.

This method provides much faster model preparation and solution than the traditional contact models since hundreds/thousands of individual refractory blocks and their contact with each other need not to be explicitly modeled. Instead, the directions for no-tension (directions of contact surface normal vectors) are needed to be defined. The benchmark simulations have proven that the solutions from the new method are very accurate.

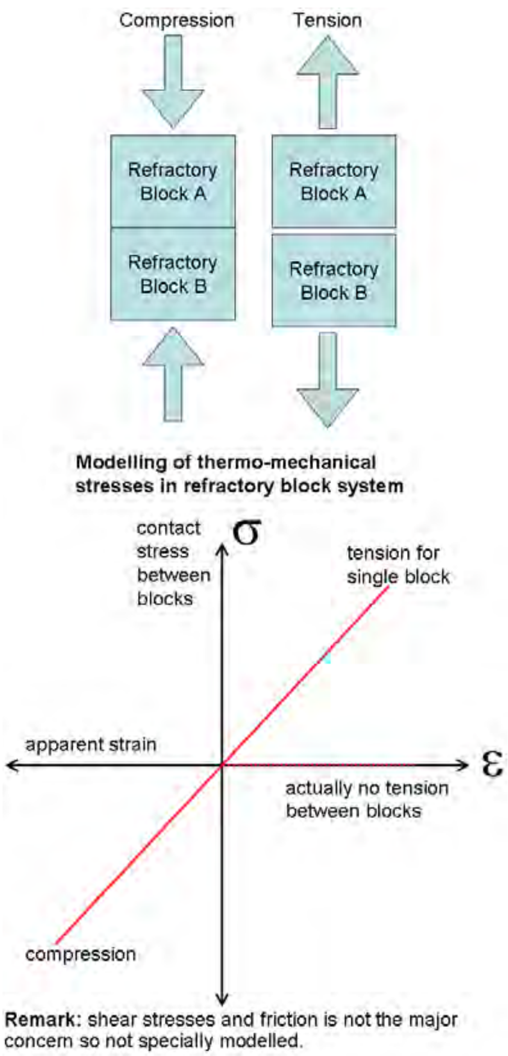

Figure 1. No tension concept.

3. Benchmark Simulations

The new simulation technique is tested for a standard circular refractory wall made up of many lining blocks and confined by using a thick steel shell at outer. A layer of the wall looks like the upper sketch in Figure 2. To make it solvable with a standard pc, the model is reduced further by using the symmetry planes passing through the center of the blocks in radial direction (see the enlarged section of the upper sketch in Figure 2). However, it should not be forgotten that such type of simplifications are very restricted to ideal case of symmetries in which the complete behavior can be downsized to the contact of two neighboring refractory blocks.

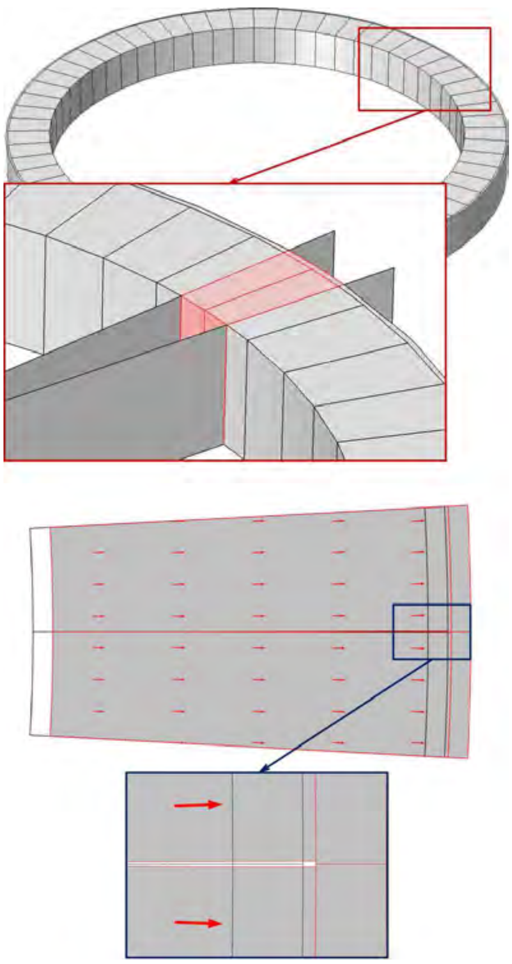

Figure 2. Separation and contact of blocks.

When the temperature is increased inside furnace, the refractory blocks expand and push each other. The assembly is hold together with the thick steel shell which undergoes a circular tension. The standard simulation considering the contact reveals the formation of gaps at outer parts of the initially perfectly fitting refractory blocks (see the enlarged section of the lower sketch in Figure 2). If any of the assumptions of a simulation model prevent to capture the formation of these gaps and their effects on the stresses/displacements, then this simulation is most probably not a realistic one.

3.1 Benchmark Model Details

Consider the above defined tube geometry is a part of an industrial furnace. The thermo-mechanical material properties are given in Table 1. Thermal boundary conditions of the problem are convection type. The inner side has a temperature of 1500°C with a heat transfer coefficient of 500W/m^2/K. The outer side has a temperature of 20°C with a heat transfer coefficient of 50W/m^2/K. In order to simplify the models, it is also assumed that there is an ideal heat transfer through the interface between the refractory blocks and steel shell. So no additional thermal resistive layer is defined. Further, the tube is assumed to behave like plane strain case (no displacement in the axial direction of tube).

Table 1: Material properties.

Property	Refractory	Steel	Unit
E	70	200	GPa
nu	0.25	0.30	-
rho	2500	7800	kg/m^3
k	15	70	W/m/K
Cp	800	450	J/kg/K
alpha	8e-6	12e-6	1/K

Three different simulation approaches have been compared in the benchmark simulations. The first approach is the continuum approach, in which the assembly of refractory blocks is treated as a continuum. In this case, there are two options: plane strain (geometry as in Figure 3) or axially symmetric (geometry as in Figure 4) models. Both models will produce exactly the same results. In this study, the second option is chosen because of its simplicity. The geometry should be defined as "Form an assembly" in COMSOL, which enables the definition of contact between refractory blocks and steel shell at internal boundary 4 in Figure 4. Corresponding contact pair should be defined in solid mechanics section. Also corresponding heat continuity pair should be defined in heat transfer section. Boundaries 2, 3, 6, 7 in Figure 4 should be assigned as symmetry.

The second approach is also a standard simulation method in which the contact of the blocks are included in the model. The simple axis symmetric model in Figure 4 cannot be used for modeling of the contact between blocks. The plane strain model given in Figure 3 must be used. The geometry should be defined as "Form an assembly" in COMSOL, which enables the definition of all contacts at internal boundaries 2, 4, 8, 10 in Figure 3. Corresponding contact pairs should be defined in solid mechanics section. Also corresponding heat continuity pairs should be defined in heat transfer section. Boundaries 1, 5, 9, 13 in Figure 3 should be assigned as symmetry.

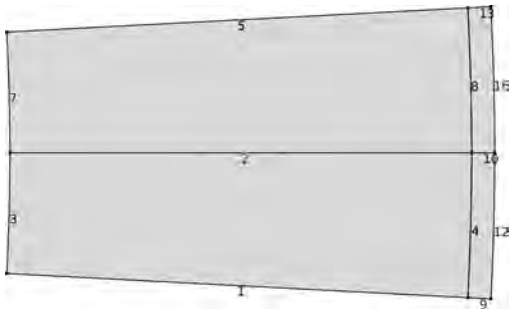

Figure 3. Layout of geometry for contact model.

Figure 4. Layout of geometry for new technique.

The third simulation approach is the new simulation technique which enables to include the effects of refractory contacts in the simplified models. The small modification to the model in the first approach can produce excellent results. The "no tension concept", which is explained in Figure 1, can be introduced in COMSOL by using initial stress and strains. The hoop stress is separately calculated and stored in a user defined variable, say S22. The user defined expression of S22 for this particular case looks like:
"solid.D12*solid.eel11 + 2*solid.D24*solid.eel12 + 2*solid.D26*solid.eel13 + solid.D22*solid.eel22 + 2*solid.D25*solid.eel23 + solid.D23*solid.eel33".
If there is a positive hoop stress (i.e., S22>0), then a negative initial stress (-S22) is introduced to cancel its effects from the actual stress tensor. This modification guaranties the elimination of the unrealistic tensile stresses between refractory blocks in hoop direction with a minimal effort.

3.2 Benchmark Model Results

The variations of hoop stresses in the refractory blocks for the three different simulation approaches are compared in Figure 5. The blue line is obtained from the standard axis symmetric model which does not consider the contact. In this case the assembly of the refractory blocks is regarded as continuum domain. Therefore, unrealistic tensile hoop stresses are obtained at the steel shell side of the blocks. The hoop stress variations obtained from the standard contact model (the red line through the center of the block and green line through the contact boundary) do not have these unrealistic tensile stresses. It is also possible to conclude that the hoop stresses at the block center and contact boundary are very similar. Finally, the introduced method (the purple line) provides a much faster model preparation and solution than the traditional contact models with an excellent accuracy.

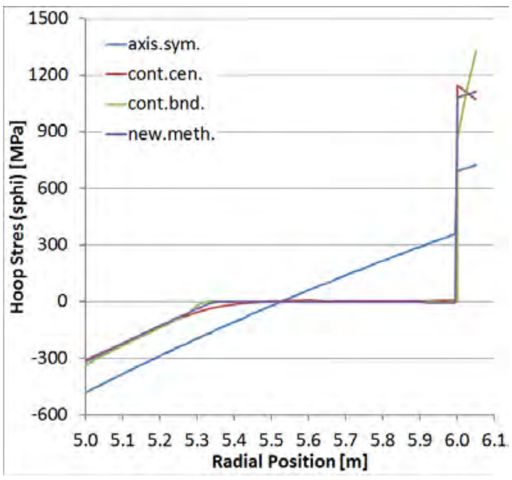

Figure 5. Comparison of hoop stresses.

4. Conclusions

COMSOL can be effectively utilized with the introduced method as an efficient tool for the computation of thermo-mechanical state of refractory linings under various conditions for blast furnaces, converters, lathes, etc. As the new method is very fast, the engineers can analyze the behavior of the lining for various geometries design and materials to develop better refractory lining concepts. The introduced solution is applicable to all two- or three-dimensional simulation models without any restriction.

5. References

1. COMSOL, *Heat Transfer Module User's Guide*, COMSOL 4.2 (2011)
2. COMSOL, *Structural Mechanics Module User's Guide*, COMSOL 4.2 (2011)

6. Acknowledgements

The author would like to thank Dr. Thorsten Hauck, Dr. Rongshan Lin, Dr. Harald Rausch, and Dr. Alex Sami Zaimi for their supports, fruitful discussions and valuable comments during the project. This work was carried out with a financial grant from the Research Fund for Coal and Steel of the European Community with project number: RFSR-CT-2007-00001.