Thermal stress analysis of refractory linings in a hot blast stove

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Abstract. The functions of hot blast stoves are to transfer the waste heat in the exhaust gas from a blast furnace to checker bricks in the center of a hot blast stove, then transfer the heat from the elevated checker bricks to newly input fresh air. After that, the heated fresh air is sent back to the blast furnace to continue the chemical reaction. Heat exchange is performed by the checker bricks and the refractory silica bricks at inner layer of linings. The middle layer of the linings is composed of refractory insulation bricks and outer layer is covered with a steel shell to maintain structural stability. Refractory bricks are brittle materials, and their allowable tensile strength is low. A finite element software ANSYS APDL is used to analyse heat transfer in the multi-layer refractory bricks. The temperature distribution in the refractory bricks in the radial direction are obtained. Thermal stress and strain in the refractory linings are investigated to design the layout of the refractory bricks and the space width between the insulation bricks. The results show that if the gas temperature near the inner surface of the linings is 1250°C, the total thickness of the insulation bricks in the radial direction should be larger than 420 mm to make the surface temperature of the steel shell lower than 120°C. The simulation results can be used as a guideline for the refractory linings design.

1. Introduction
In steel-making processes, iron ore and coke are used in a blast furnace to produce molten iron, and then the molten iron is transported to a converter for subsequent steel-making procedures. During the chemical reaction in the blast furnace, heated fresh air is poured into the blast furnace in a high temperature environment to cause incomplete combustion reaction with the coke and generate carbon monoxide, which is used to deoxygenize the raw iron ore and generates molten iron. Carbon dioxide and residual gas are exhausted. In order to reuse the waste heat, most blast furnaces are equipped with a hot blast stove, which utilize checker bricks to absorb the heat from the exhaust gas and then use the elevated checker bricks to heat new fresh air to a specified temperature. Then, sent the heated new fresh air back to the blast furnace. While the hot blast stove implements heat absorption operation, the temperature difference between the inner and outer surfaces of the lining reaches more than one thousand degrees Celsius. If the structural design is not appropriate, the refractory materials in the linings properly generate crack, even cause damage due to thermal stress. Some papers have been presented to discuss the heat transfer and the thermal stresses in a hot blast stove. Yang [1] established a thermal-fluid model for an external combustion type of hot blast stove, in which the checker chamber is filled with checker bricks. A finite element software “Fluent” is used to simulate the flow rate and temperature distribution of the gas within the checker chamber and combustion chamber in a hot blast stove. Gruber et al. [2] established a finite element model at the bottom part of a blast furnace,
and conducted thermal stress analysis to investigate the effects of material parameters of the castable refractory materials on the life of the furnace. It is concluded that the thickness and compressibility of the castable refractory materials are important parameters to avoid excessive pressure at the bottom of the blast furnace. Liu [3] established a solid model of the 3D blast furnace with a CAD software, and then used a finite element software COMSOL Multiphysics to analyse the transient heat transfer and thermal stress of carbon bricks before and after the molten iron flows out from the blast furnace. Hassleman [4] discussed problems of material selection for engineering design involving thermal stress fracture and crack propagation briefly. The author used a diagram of remaining strength of a brittle solid as a function of the severity of thermal shock to illustrate selections of the thermal stress fracture resistance parameter for the proper interpretation of thermal shock data. Boccaccini et al. [5] used chevron scotch refractory specimens to perform experiments to obtain fracture values of refractories after thermal cycling. Zetterholm et al. [6] established a mathematical model to calculate the heat transfer efficiency during the operations of a hot blast stove and improved the energy efficiency of steelmaking. Yan and Cheng [7] established a three dimension mathematical model to analyse the stress distributions and deformations of the shell of a hot blast stove. The deformation of the shell might result in a gap between the shell and the refractory material, which may damage the safety and stability of the hot blast stove. Up to now, few papers discussed the thermal stresses inside the refractory linings materials in a hot blast stove. The objective of this paper is to investigate the temperature distributions and thermal stresses inside the refractory linings of a hot blast stove with finite element analyses.

Figure 1. Schematic diagram of the hot blast stove.

2. Finite element analysis

This objective of this paper is to investigate the temperature and thermal stresses inside the refractory linings of a hot blast stove. The construction of a hot blast stove is shown in Figure 1. External combustion type hot blast stoves are composed of a checker chamber and a combustion chamber, and they are connected by a crossover. When the hot blast stove is in operation, the exhaust gas from the blast furnace flows into the combustion chamber to exchange heat with the checker bricks in the checker chamber. The high temperature of the gas inside the hot blast stove causes thermal stresses occurred in refractory linings. The general structure diagram of the refractory lining is shown in Figure 2. It is composed of silica bricks, insulation bricks and steel shell. There are gaps between brick layers. Symbols $B_s$, $B_i$ and $S$ in the model diagrams represent the silica brick, insulation bricks and steel shell respectively. Sometimes if the gaps between the brick layers are too large, ceramic blankets can be inserted into the gaps to avoid the air flowing turbulenty. To obtain temperature and thermal stresses distributions in the refractory linings, finite element software “ANSYS APDL” is used in this study. Mesh types of solid 70 was selected during temperature distribution simulations. Mesh types of solid
185 was selected during thermal stress distribution simulations. In this paper, all objects were meshed as hexahedral elements. Elements sizes can be input manually with a maximum side length of the elements or automesh function is used for mortar. After defining the boundary conditions, simulations start. After the simulation is completed, the results can be shown with post-processor.

![Figure 2. Structure diagram of refractory lining.](image)

2.1. Modelling and mesh configurations in bricks and mortar
Refractory linings are made up of refractory bricks and mortars. Based on CNS-612 [8], the dimensions of standard cuboid brick and trapezoid brick used in this paper are shown in Figure 3. They are used for construction for both silica bricks and insulation bricks. Standard cuboid brick type is used to construct the insulation bricks for simulations of temperature distribution to be discussed in Section 3.2. This paper mainly used trapezoid bricks to establish partial refractory linings models. In addition, mortar is used to bond the refractory bricks. The thickness of mortars is fixed at 2 mm. The mesh configurations in bricks and steel shell are shown in Figure 4. There are two layers of the silica bricks and insulation bricks in axial direction. According to convergence analyses, the relative errors for element lengths of 10 and 12 mm are smaller than 0.27% . Therefore, element side length was set to be equal or less than 10 mm. There are three layers of elements in the steel shell in the thickness direction. Because the thickness of mortar is much smaller than the element length. If the mortar is indicated in the modelling, a large number of elements is required, and simulation will be increased dramatically. To save the simulation time, mortar is not included in this case. The effect of inclusion of mortar is discussed in Section 3.4.

![Figure 3. Refractory bricks size diagram.](image)

![Figure 4. Mesh configurations in refractory linings.](image)
2.2. Material properties

The material parameters used in the simulations are summarized in Table 1. Some parameters are functions of the temperature. Generally, the thermal conductivity of silica brick increases linearly with the temperature.

Table 1. Summary of material properties.

| Material       | Thermal conductivity (W·m⁻¹·K⁻¹) | Modulus of elasticity (GPa) | Poisson ratio | Thermal expansion coefficient (10⁻⁶) |
|----------------|----------------------------------|-----------------------------|---------------|-------------------------------------|
| Silica brick   | $K_S(T)$                         | $E_S(T)$                    | 0.2           | 12.5                                |
| Insulation brick | $K_I(T)$                         | $E_I(1.42)$                 | 0.2           | 5.5                                 |
| Motar         | N/A                              | $E_M(T)$                    | 0.25          | 14.5                                |
| Steel shell   | 36.6                             | 211                         | 0.3           | 10.6                                |

3. Simulation results and discussions

This section is divided into four parts. In the first part, thermal stresses distributions in the refractory linings are discussed based on the conditions shown in Figure 4. In the second part, the effects of the insulation brick layer number on the temperature distribution of the refractory linings are discussed. In the third part, the effects of the gap width between brick layers on the thermal stresses inside the bricks are discussed. In the fourth part, thermal stresses inside the bricks including mortar in the refractory linings or not are discussed.

3.1. Temperature and thermal stress distributions at high temperature zone of checker chamber

In order to reduce the number of the elements, 1/72 symmetric geometry (shown in Figure 4) in the FE simulation. The outer diameter of the steel shell is fixed at 5 m. The radial thickness of the silica brick is fixed to 230 mm and steel shell is fixed to 25 mm. There are three layers of insulation bricks used in this model. $W_g(g_1, g_2, g_3, g_4)$ indicates the width of the gaps as shown in Figure 4. In this section, a $W_g(6, 6, 6, 6)$ model was established. The maximum element size is 10 mm. Gas near the inner wall of the straight portion in the checker chamber is about 1250°C. Therefore, the simulated boundary conditions are set as follows: Inner surface temperature of the lining is 1250°C. Natural convection coefficient of the outer surface of the lining is 10 (W/m²·K) and the atmospheric temperature is 25°C.

The surfaces at the at the upper and lower, or the both sides of the refractory linings are set as adiabatic boundary.

Temperature distributions in the radial direction are shown in Figure 5. The simulation results of temperature distributions are the boundary conditions for subsequent stress analysis. The boundary conditions of displacement at the hoop direction and that at the bottom surface are set as zero. The maximal tensile principal stress distributions are shown in Figure 6.

Figure 5. Temperature distributions in the radial direction inside the refractory linings (unit: °C).
3.2. Effects of insulation brick layer number on thermal stress distribution

Hot blast stove linings are multi-layer hollow cylinder. The thickness of the mortar is about 2 mm, and its size compared with the thickness of the refractory brick is very small. Mortar’s effects on the temperature distribution are ignored in this study. A 1/4 symmetric model is adopted for simulations. Figure 7 shows the furnace lining model for temperature distribution. The outer diameter of the refractory linings is fixed at 5 m. The radial thicknesses of the silica brick and steel shell are the same of those in Section 3.1. The cuboid bricks are used for insulation brick layers. The radial thickness of the insulating brick is 65 mm/layer. Maximum element size is set as 25 mm for all the refractory linings. The effect of layer number of the insulation bricks (N value) on the temperature distribution of the refractory lining are discussed. The temperature boundary conditions are the same as those used in Section 3.1.

The temperature distribution simulation results at different positions are shown in Table 2. P₁, P₂ and P₃ denote the interface between silica bricks and insulation bricks, insulation bricks and steel shell, and the outer surface, respectively. As the number of insulation bricks increases, the temperature gradient of the refractory material gradually decreases, and the surface temperature of the steel shell becomes lower. However, for each additional layer of insulation bricks, the surface temperature reduction at the steel shell gradually decreases.

![Figure 7. One-fourth symmetry linings model for temperature distribution simulations (unit: mm).](image)

| R₁=5m , Tᵣ₀=1250°C | P₁ | Interface temperature | P₂ | P₃ |
|---------------------|----|-----------------------|----|----|
| 5                   | 1097.93 | 147.18 | 146.35 |
| 7                   | 1133.12 | 116.98 | 116.36 |
| 9                   | 1154.51 | 98.32  | 97.82  |
| 11                  | 1168.84 | 85.63  | 85.22  |
3.3. Effects of gap width of refractory linings on thermal stress distribution
The geometry configurations of the refractory linings are the same as those in Section 3.1 and shown in Figure 4. The temperature distribution in Figure 5 is used. Boundary conditions for thermal stress distributions simulations are the same as those used in Section 3.1. Table 3 shows the simulation results of the lining stress analysis under different gaps. It can be seen that the minimum principal stress will decrease and the maximum principal stress will increase when the reserved seam increases.

Table 3. Simulation results under different reserved seam widths (unit: MPa).

| Model          | Silica brick |  |  | Insulation brick |  |
|----------------|--------------|---|---|------------------|---|
|                | Maximum      | Maximum | Maximum | compressive stress |  |
|                | tensile stress | compressive stress | tensile stress |  |
| Gap(4,4,4,4)   | 0.34         | -39.5    | 3.68    | -2.45            |  |
| Gap(5,5,5,5)   | 0.33         | -36.4    | 3.74    | -2.25            |  |
| Gap(6,6,6,6)   | 0.33         | -33.4    | 3.8     | -2.1             |  |

3.4. Influence of mortars on stress distribution of refractory lining
Figure 8 is a schematic diagram of the refractory linings with mortars. The geometry configurations are the same as those in Figure 4. The gap widths are set as Wg (4, 4, 4, 4), which can get a minimum tensile stress. The upper and lower layers are stacked with unalignment in order to avoid stress concentration. The temperature and force boundary conditions are the same as those used in Section 3.1. The temperature distributions inside the refractory linings are shown in Figure 5. Only the stress values at the lowest refractory brick and mortar of the model were shown in Table 4, because the boundary condition at the lowest refractory brick is closer to the real situation. It is found that if mortars are included in the geometric model, the principal stresses inside the bricks become larger than those without mortar. In addition, from compression tests [9], the allowable compressive stress of the silica brick and insulation brick are about -38 and -5 MPa, respectively. From the results in Tables 3 and 4, it is known that the case for gap widths of Wg(4, 4, 4, 4) without mortar will probably lead to fracture due to excessive compressive stresses.

Table 4. Simulation results of stress distribution with mortar (unit: MPa).

| Wg (4,4,4,4) | Silica brick |  |  | Insulation brick |  |
|--------------|--------------|---|---|------------------|---|
|               | Maximum      | Maximum | Maximum | compressive stress |  |
|               | tensile stress | compressive stress | tensile stress |  |
| With mortar   | 2.61         | -12.4   | 2.21    | -3.19            |  |
| Without mortar| 0.34         | -39.5   | 3.68    | -2.45            |  |

4. Conclusions
A finite element software ANSYS APDL was used to conduct heat transfer analyses and simulations of thermal stress distributions in the refractory linings. The heat transfer simulation results at the high temperature zone in the refractory linings show that the increase in the insulation bricks number...
reduces the temperature gradient of the refractory brick and the surface temperature of the steel shell. If the gas temperature near the inner surface of the linings is 1250°C, the total thickness of the insulation bricks in the radial direction should be larger than 420 mm to make the surface temperature of the steel shell lower than 120°C. In addition, from the simulation results of thermal stress distributions, it is known that the increase in the gap width can reduce the compressive stress inside the refractory bricks, but the tensile stresses inside the refractory bricks will increase. The geometry design for gap widths of \( W_g \ (4, 4, 4, 4) \) without mortar may lead to fracture due to excessive compressive stresses.

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