Nonlinear Numerical Simulation of Service Behaviour of Regenerative Burner under Multiple Thermal Shocks

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Abstract. In order to explore the service behaviour of regenerative burner parts, the burner refractory was studied experimentally and thus a series of temperature-related material performance parameters were obtained. A method for calculating the Young's modulus of materials between two thermal shocks was proposed by combining the law of Young's modulus varying with temperature and that of residual Young's modulus varying with the quantity of thermal shocks. The service process of the burner under the condition of multiple thermal shocks was nonlinearly simulated by using the obtained parameters. The results show that the thermal load of regenerative burner in stable service is about 0.55 MPa, that is much less than the previous result without considering the material nonlinear characteristics, 37MPa.

1. Instruction
Cyclic thermal loads experienced in service by refractory parts often lead to thermal fatigue failure. Regenerative burner is a typical example. According to the principle of regenerative heating technology, the regenerative burner, one of the key parts of regenerative heating furnace, get damaged frequently due to thermal fatigue fracture, which resulted in a short working life of the furnaces [1, 2]. Therefore, a great deal of research has been done on the damage mechanism of refractories [3-6]. The study of service behaviour of refractory parts is an important work.

However, because the refractory part is in a high temperature working state for long time, the various parameters of the refractory part are difficult to monitor in real time. Therefore, using numerical simulation technology has become a very effective research method, which plays a great auxiliary role in the study of such problems, and will neither lead to production delay, and risk of failure nor get restricted by extreme conditions in production operation.

In terms of numerical simulation of service behaviour of the refractory parts, many achievements have been made in previous researches [7-11]. However, in the previous work, the effects of thermal shock cycle and nonlinear material performance on parts are not considered, and therefore the performance analysis of refractory parts is not accurate and reliable enough.

2. The Material of the Regenerative Burner
The regenerative burner is made of refractory, the chemical compositions of which are shown in the Table 1.
Table 1. Chemical compositions of the refractory (%).

|             | Al$_2$O$_3$ | SiO$_2$ | Al(H$_2$PO$_4$)$_3$ | Fe$_2$O$_3$ | TiO$_2$ | CaO | MgO | K$_2$O | Na$_2$O |
|-------------|-------------|---------|---------------------|-------------|---------|-----|-----|--------|--------|
| Content (%) | 75.6        | 16.8    | 5.5                 | 0.4         | 0.95    | 0.23| 0.19| 0.18   | 0.15   |

3. High-temperature Properties of the Refractory

Current studies have shown that, in the service process of refractory parts, many parameters of refractory properties vary with the temperature [11-13]. With the aim of exploring the service behaviour of refractory parts, it is necessary to determine such laws.

3.1. Thermal Expansion Coefficient Values of the Refractory

According to the GB/T 7320-2008, the thermal expansion coefficient values of the refractory from room temperature to 1350°C were measured experimentally, and the results are shown in Figure 1.

![Figure 1. Thermal expansion coefficient values of the refractory.](image)

3.2. The Thermal Conductivity Values of the Refractory

According to the GB/T 5990-2006, the thermal conductivity values of the refractory from 200°C to 1000°C were experimentally determined, as shown in Table 2.

| Temperature (°C) | 200   | 400   | 600   | 800   | 1000  |
|-----------------|-------|-------|-------|-------|-------|
| Thermal conductivity (W/(m·K)) | 0.746 | 0.845 | 0.904 | 0.906 | 0.903 |

It can be seen from Table 2 that the thermal conductivity values of the refractory are basically unchanged when T≥600°C. Therefore, a constant can be used in numerical simulations.

3.3. The Heat Capacity Values of the Refractory

The heat capacity values of the refractory were measured experimentally, the results are shown in Table 3.

| Temperature (°C) | 500   | 700   | 800   | 1000  |
|-----------------|-------|-------|-------|-------|
| Heat capacity (J/(g·K)) | 1.263 | 1.266 | 1.271 | 1.286 |

3.4. Young's Modulus of the Refractory

3.4.1. The law of Young's modulus varying with temperatures

According to GB/T 30758-2014, the Young's modulus of unused refractory sample was measured experimentally as the temperature rose from the room temperature to 1350 °C and then cooled naturally down to the initial temperature. The test results are shown in Figure 2.
In order to facilitate numerical calculation, regression analysis was conducted, based on the measured data, to obtain the law of Young’s modulus varying with temperatures, as shown in Eq. (1):

\[
E = \begin{cases} 
0.015T + 36.81, & (R^2=0.9817) \text{ in warming period} \\
2\times10^{-5}T^2 + 0.0419T + 28.334, & (R^2=0.9849) \text{ in cooling period} 
\end{cases}
\]

where \(E\) is Young’s modulus (GPa), \(T\) is temperature (°C).

3.4.2. The law of Young’s modulus varying with the quantity of thermal shocks

Previous studies have shown that Young’s modulus and strength of refractories decrease with the increasing thermal shocks [12]. This phenomenon obviously affects the service behaviour of refractory parts, but in the previous numerical simulation studies, the law of Young’s modulus varying with the quantity of thermal shocks was usually not considered. In order to overcome this shortcoming, many tests have been done to determine such law in this work. The thermal shock tests of refractory were carried out by means of an air cooling method which is more close to the actual production conditions.

Six strip samples (160×40×40 mm\(^3\)) were prepared from the same batch of firebricks for the thermal shock tests. They were heated in a heating furnace at the heating rate of 100 °C/h. When heated to 1300°C, they were taken out, sprayed with 800°C air for 48s and then put back into the heating furnace for 48s. Such a cycle was repeated dozens of times thereafter. After every cycle, Young’s modulus of every sample was measured when the sample cooled down to room temperature, and the measured values were averaged. A total of 60 cycles were performed and results are shown in Figure 3.

It can be seen in Figure 3 that the residual Young’s modulus of the sample decreases sharply during the first 5-7 cycles, and then gently afterwards. After about 20 thermal shock cycles, the value
continues to decrease, but no longer significantly. After regression analysis on measured data, the law of \( E_D \), residual Young’s modulus, varying with \( N \), the quantity of thermal shock cycles, was obtained, as shown in Eq. (2):

\[
E_D = 0.0006N^4 - 0.00415N^3 + 0.9719N^2 - 9.5987N + 40.101, \quad R^2 = 0.9879
\]  

(2)

The internal channel surface of the burner part is affected by the internal fluid temperature, which fluctuates between 1300°C and 800°C with an interval of 48s. At present, it is impossible to measure the change of Young’s modulus value continuously in the thermal shock test of the refractory. Therefore, the approximation of the Young’s modulus of the refractory was derived by using the Young’s modulus values measured continuously and the residual Young’s modulus values measured after multiple thermal shocks, and it is used for the numerical simulation of continuous thermal shock process. According to Figure 2, the Young’s modulus of the refractory varied with temperatures. According to Figure 3, after each thermal shock, the residual Young’s modulus value of the refractory actually decreased. It can be found that the relationship of \( E \) varying with \( T \) during the heating and cooling period of each thermal shock remains similar to that shown in Figure 2. However, after each thermal shock, the \( E_D \) value at each temperature point should be reduced correspondingly. The extent of each reduction is determined according to the values in Figure 3, with the schematic diagram shown in Figure 4.

Since the material is not cooled to room temperature and then reheated, but cooled by the 800°C air for 48s and then heated by the 1300°C air for 48s, it can be held that the values of Young’s modulus between two thermal shocks are determined by the solid line in Figure 4. In this way, in each thermal shock cycle, the values of Young’s modulus can be obtained according to the law presented in Figure 3 and Figure 4, and then substituted into the numerical calculation.

![Figure 4](image-url)  

**Figure 4.** The schematic diagram of the values of Young’s modulus between two thermal shocks.

4. **Numerical Simulation**

The transient numerical simulation was carried out according to the nonlinear parameters discussed above. At first, the transient temperature field of the burner was simulated according to the actual furnace baking curve. Then the distribution of temperature field after baking was taken as the initial condition to simulate the service process of the regenerative burner. After the initial temperature field was obtained, the thermal-structural coupled numerical simulation of the service behaviour of the burner under multiple thermal shocks was carried out. The flow of numerical simulation is shown in Figure 5. For specific methods, please refer to Literature 7-9 attached. Because the Young’s modulus of the refractory changed slightly after 20 thermal shock cycles, only the first 20 were simulated. Since the quantity of cycles is a bit too large, only one part of the flow is shown in Figure 5.
5. Results and Discussion

During a commutation period, the burner part has the process of preheating gas entering and high-temperature exhaust gas discharging. Therefore, the working process of the burner in a commutation period can be divided into two periods: gas combustion period and smoke extraction period. The fluid flowing through the internal passage of the burner at different periods has different temperatures.

For refractory parts, the factors that affect their service performance and service life mainly include maximum stress and stress amplitude. The stress amplitude discussed is the stress difference caused by the condition change at the same position of the part. Because the transient analysis is carried out, the temperature field and stress field in the part vary constantly with time, the node location that produces the maximum stress amplitude is not unique. The maximum stress amplitude and node position can be determined by traversing the stress value of all nodes over time. The variation laws of the maximum stress and the maximum stress amplitude in the burner are shown in Figure 6 and Figure 7 respectively.

It can be seen from the numerical simulation results that with the increase of the quantity of thermal shocks, the maximum thermal stress of the burner in the gas combustion and smoke extraction periods decreased, and the reduction of the maximum thermal stress was not obvious after 20 cycles. Similarly, the maximum stress amplitude of the burner also decreased with the increase of the quantity of thermal shocks, and was basically kept unchanged after about 20 times, with a value of about 0.55Mpa. The burner is in a stable working condition.

Compared with the calculation results of my previous study [9], the maximum thermal stress and maximum thermal stress amplitude load of refractory parts during stable service process are much less,
when the nonlinear characteristics of refractory are considered. The numerical simulation results also show that the position of maximum thermal stress amplitude in the burner is not that of maximum thermal stress in the burner.

6. Conclusions
The experimental study of regenerative burner refractory was carried out, and the nonlinear characteristic parameters of the refractory at high temperature and their relationship with thermal shock were obtained. The law of the Young’s modulus varying with temperatures combined with that of the residual Young’s modulus varying with the quantity of thermal shocks to deduce the values of Young’s modulus between two thermal shocks. And the obtained parameters are used in the nonlinear numerical simulation calculation of continuous thermal shock process. The results show that the thermal load of refractory parts in stable service is about 0.55 MPa, that is much less than the previous result without considering the nonlinear properties of burner refractory, about 37 MPa [8]. It is obviously inappropriate to characterize the long-term service behaviour of refractory parts in relatively mild environment only through the extremely limited physical parameters which were measured in very short time or under harsh conditions. In the performance evaluation and life prediction of refractory parts, more accurate results can be obtained by considering the nonlinear properties of the refractory.

7. References
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