Numerical Simulation Study on Failure of Graphite Heat Exchanger with Orifice Block

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Abstract. Phenolic impregnated graphite is a new kind of material with higher corrosion resistance and thermal conductivity. In the chemical industry, it is often used to make containers and pipes containing strong acid and alkali medium. It is the characteristic of phenolic resin impregnated graphite heat exchanger that the corrosion resistance and heat transfer efficiency of the heat exchanger are greatly improved. In this paper, a failure case of graphite heat exchanger in a chemical enterprise in Shanghai was analyzed by numerical simulation. According to the actual working conditions, the temperature field and flow field in the porous graphite heat exchanger were numerically simulated. The numerical simulation results of temperature field showed that the graphite block would be subject to thermal shock when the equipment was started and shut down, resulting in the increase of temperature difference of graphite block. In addition, the pre-tightening force of the flange of graphite heat exchanger was simulated by numerical simulation, and it was found that the position of stress concentration coincided with the crack position of actual failure, and the improvement suggestions were put forward for the structural design of graphite block.

Keywords: Pressure vessel, Impregnated graphite, Numerical simulation, Failure.

1. Introduction
Phenolic resin impregnated graphite has been used to produce heat exchange equipment with various structures due to its excellent corrosion resistance and thermal conductivity. The porous block heat exchanger is widely used in chemical industry due to its compact structure and high heat transfer efficiency. The core component of the graphite heat exchanger block is that after sintering fine particles of graphite, the flow pipes of shell side and tube side are machined, and then the phenolic resin is impregnated at high temperature and high pressure to fill the pores between the graphite. The phenolic resin of graphite pore filling material is usually high density, but the use temperature is low, and the linear expansion coefficient is about 10 times of graphite material [4]. Graphite itself is a kind of brittle material, after impregnation with phenolic resin, as a new material, the research on this new material is relatively less. Therefore, it is of great significance to study the failure mode and failure mechanism of such materials to ensure the safe and long-term operation of graphite impregnated pressure vessels [5].
2. Equipment and process conditions
Equipment and process conditions overview failure equipment for a hydrochloric acid purification reboiler of a chemical enterprise, which plays a role in removing chlorine impurities in hydrochloric acid. The failure of this equipment makes the system unable to guarantee the recycling of hydrochloric acid and the purity of products. The assembly drawing of the equipment is shown in Fig. 1. The equipment is composed of three identical graphite blocks connected up and down. The sealing between graphite blocks is realized by PTFE gasket. Among them, S1 is the service side inlet, S2 is the service side outlet, T1 is the process side inlet, T2 is the process side outlet. At the top of port T2, the graphite block is the one with the most failure

![Figure 1. Assembly drawing of HCl purification Reboiler](image)

Table 1. Materials of main pressure components

| Material variety       | Material brand | Standard      | Supply status |
|------------------------|----------------|---------------|---------------|
| Plate                  | Q345R          | GB713-2014    | Hot-rolling   |
| Forging                | 16MnII         | NB/T47008-2010| Normalizing   |
| Head,Graphite block    | GRAPHILOR XB   | GB/T21432-2008| Grade A       |

The materials of the main pressure components of the equipment are shown in Table 1. The main design parameters are as follows: shell side design pressure 0.6MPa, working pressure 0.011mpa, design temperature 120 ℃, working temperature 102 ℃; design pressure 0.9mpa, working pressure 0.6MPa, design temperature 245 ℃, working temperature 165 ℃; shell side medium is steam, medium of tube side is hydrogen chloride, water and trace chlorine.

3. Macroscopic morphology of failure graphite block
Remove the top failure graphite block, and the overall morphology of the failure part is shown in Fig. 3. It can be seen that from the tube side hole on the edge of the block, there is a crack throughout the height of the graphite block, and the material peeling phenomenon appears in each small hole in the shell side. According to the observation, there are two failure modes of the failure part: one is crack failure through the whole graphite, as shown in Fig. 2 (a); the other is graphite spalling failure of each shell side hole, as shown in Fig. 2 (b).
Figure 2. Overall morphology of cracked graphite block

Figure 3. Specific failure modes of graphite heat exchanger block

Because graphite itself is a brittle material. It is suspected that the through crack on the graphite block is caused by mechanical force. For the case of small hole burst, further analysis is needed. Due to the complexity of the internal structure of the porous graphite heat exchanger, the distribution of the internal flow field is unknown. The stress distribution of the round graphite block after machining is not clear. Therefore, after observing the specific failure morphology of the graphite block, the failure analysis of the container was carried out with numerical simulation.

4. Finite element modeling and numerical analysis

Different from the common shell and tube heat exchanger, the shell side of the hole block graphite heat exchanger is composed of the shell and the flow space of the small holes in the graphite block, and the tube side is mainly composed of the flow space of the large holes in the graphite block. The flow direction of the medium in the tube side is vertical, while the flow in the shell side is more complex. The overall flow pattern is S-shaped, and the adjacent graphite blocks are separated by semicircular PTFE gaskets. In order to study the flow of shell side medium between adjacent graphite blocks, two adjacent graphite blocks were established according to the ratio of 1:1, and the shell body and the inlet and outlet of shell medium were established according to the actual size. Such a modeling scheme takes into account the simplicity of calculation and the reasonable simplification of the model, which will not affect the analysis of the fluid flow in the shell. The model of graphite heat exchanger block and the model of integral assembly are shown in Fig. 4 and Fig. 5.
In the model, the solid mesh of hexahedron is used for graphite block and metal shell, and tetrahedral mesh is used for flow space of tube side and shell side. There are 17288 solid meshes and 152404 tetrahedral meshes.

4.1. Flow field analysis
Set the flow space of the whole shell side as the calculation domain of fluid, set the shell material iron as solid material 1, the thermal conductivity is 80W / m.k, and the specific heat capacity is 460J/ kg. K. Two graphite blocks were set as solid material 2, the thermal conductivity was 151w / m.k, and the specific heat capacity was 710J / kg. K. Set the boundary conditions of fluid calculation domain. The upper nozzle is the fluid inlet, the inlet velocity of the fluid is set at 10 m / s, the lower part is the fluid outlet, and the static pressure at the outlet is set as a standard atmospheric pressure. The global initial temperature is set as 20 ℃, the heat source is steam, and the temperature is 170 ℃.
After calculation, the streamline distribution in the shell side is shown in the figure. After entering the shell side through the pipe orifice, the steam rapidly diffuses and distributes to the chambers on both sides, and then flows into the graphite block through the small hole, and exchanges heat with the medium in the process side (in the large hole). After a heat exchange, the steam flows out of the graphite block, and enters the next layer from the right side of the shell under the action of gravity. After the steam enters the graphite block again from the right side for the second heat exchange with the medium at the process side, the steam flows out of the heat exchanger through the fluid outlet.

![Figure 6. Streamline distribution of porous graphite heat exchanger](image)

It should be noted that the flow space of the shell on the left and right sides in Fig. 7 is blocked by the plates on the graphite block. Through this structure design, the fluid in the service side and the process side can be heat exchanged for many times, so as to improve the heat exchange efficiency.

Through the further streamline analysis of shell fluid, it can be seen that after the fluid flows from the upper layer to the next layer of graphite block, the vortex will form under the lower layer of graphite block near the stop block. Such a long time of scouring may cause erosion and corrosion to the graphite block. In this paper, the actual failure parts will be analyzed in detail.

### 4.2. Analysis of transient temperature field

Research [7] shows that the linear expansion coefficient of phenolic resin is more than 10 times that of graphite material. If the graphite block is heated directly, it may impregnate the resin part on the surface of graphite block, resulting in great internal stress and cracking of graphite block. For the perforated graphite heat exchanger, the heat brought by steam can be transferred to hydrochloric acid at the process side under normal working conditions, so as to ensure that the graphite block works at the normal working temperature. Under special circumstances, such as the start-up and shutdown, the medium input time of shell side and tube side is not uniform, which may cause the graphite block short-term over temperature and cause graphite block cracking.

Based on the above analysis, the transient thermal analysis and calculation of the temperature field in the graphite heat exchanger under the start-up and shutdown conditions, that is, when the medium is
not connected to the process side, is carried out to observe the temperature distribution in the calculation domain under the extreme conditions.

In the transient thermal analysis, the grid division and calculation domain setting are consistent with the flow field simulation. The heat source is the volume heat source at the steam inlet. The initial temperature is set at 20 °C, the steam temperature is 170 °C, the time distribution is 1, and the number of sub steps is 50. The calculation results are shown in Fig. 7.

![Figure 7. Transient temperature distribution of heat exchanger](image1)

From the top view of the height of the steam inlet of the heat exchanger, the heat diffuses with the steam to the direction with less flow resistance in the initial period of time. Combined with the side view of the position of the steam inlet nozzle, the heat diffuses up and down at the same time, and diffuses more downward under the action of gravity. Under the action of pressure, the steam begins to pass through the hole to the other side of the inlet. After analyzing the temperature distribution nephogram of impregnated graphite block in detail, it can be seen that when the temperature of graphite material in the hole increases, the temperature of the hole edge facing the steam inlet side begins to increase due to heat accumulation, and the temperature difference between the hole and surrounding materials also increases. According to the temperature distribution cloud chart, the temperature rise is more obvious at the side where the hole is far away from the steam inlet, and the temperature difference between the hole and the surrounding materials is more obvious. It also increases the risk of cracking of impregnated graphite materials.

![Figure 8. Temperature distribution of impregnated graphite heat exchanger block](image2)
As time goes on, the steam entering the opposite side of the nozzle gradually increases, and the temperature of the graphite block also rises rapidly, which is similar to the graphite block on the other side. The temperature rise is more significant in the direction where the edge of the small hole is far away from the nozzle. From the temperature distribution cloud chart of the graphite block surface, we can clearly see the temperature rise of the graphite material on the side of the hole edge away from the nozzle the height is more obvious. It is particularly concerned about whether the material will be cracked due to excessive temperature difference.

4.3. Analysis of flange preload

Because graphite is a brittle material, it is likely to be damaged by external mechanical force. In practical use, the impregnated graphite block is fastened by bolts. The graphite blocks are sealed by PTFE gasket. In the process of installation and use, the graphite block may be damaged due to uneven pressing force or external force impact in use. This situation is strictly controlled in use [8, 9]. Another failure reason may be the structural design of graphite block itself. Although the graphite block itself is a cylinder with regular shape, its mechanical strength is weakened to varying degrees after the shell and tube are drilled. When the original uniform compression load is loaded on the graphite block, the displacement in different directions is different. Therefore, it is of great significance to study the mechanical response of the graphite block after drilling.

In this paper, according to the size modeling of the actual failure graphite block, uniform load is applied to simulate the bolt compression force in the 4mm area of the circular graphite block edge, and the full constraint is applied at the bottom edge of the graphite block to solve the static problem. The simulation results are shown in Fig. 9.

![Figure 9. Application of load constraints on porous graphite](image-url)
From the simulation results, it can be seen that due to the weakening of the structural strength of the graphite block by drilling, the displacement of the graphite block edge is different under the action of uniform load, and the maximum displacement occurs at the position near the edge of the outermost side of the large hole. Therefore, for this type of graphite block, this angle is more likely to be damaged under the action of pressure.

5. Comparison between numerical analysis results and failure parts
In the actual case, there are two pieces of graphite through the edge of the failure. By comparing the crack location with the results of static analysis of graphite block, it can be concluded that the crack location is very close to the maximum displacement position obtained by simulation, which further verifies the accuracy of the simulation results.

The results show that most of the spalling occurs at the side of the orifice far away from the nozzle. When the graphite block with the same type and short service time is observed in the field (as shown in Fig. 11), the material at the edge of the small hole far away from the nozzle can also be observed to peel off.

![Figure 10. Simulation displacement distribution of pressing force of hole block graphite block](image)

**Figure 10.** Simulation displacement distribution of pressing force of hole block graphite block

![Figure 11. Spalling of small hole material of graphite block in short term service](image)

**Figure 11.** Spalling of small hole material of graphite block in short term service

It can be seen that the spalling phenomenon of this material is mainly caused by the thermal shock when the hot coal medium passes through the steel. Further observation on the spalling of the small holes in the failure graphite block shows that there is spalling in the lower hole, but not in the graphite block with short service time. Combined with the simulation results of the flow field in the heat exchanger, it is considered that the vortex erosion at the bottom of the graphite block is the reason for
the further spalling of the material inside the small hole. The long-term erosion of the vortex leads to the exfoliation of the graphite material in the small hole.

6. Conclusion and suggestion
In this paper, the flow field, temperature field and static pressure analysis of hydrochloric acid reboiler and impregnated graphite heat exchanger in a chemical enterprise are analyzed. Through the analysis and comparison of the actual failure mode and location of graphite block and the results of numerical simulation analysis, it is found that the simulation results are in good agreement with the actual situation. There are three main reasons for the failure of the graphite heat exchanger.

(1) The structural strength of the graphite block itself is weakened in varying degrees after the impregnated graphite heat exchanger block is machined and drilled. Under the influence of uniform pressing force or some mechanical external force in the actual use process, the weak part of the graphite block has a large displacement, which leads to the graphite cracking. (2) During the start-up and shut-down of the equipment, due to the unreasonable sequence of materials passing through the tube side and shell side, the medium in the tube side has not been passed in when the steam side is connected, which will cause thermal shock to the graphite block, and large temperature difference internal stress will be produced in the area with large local temperature difference, resulting in spalling of local impregnated graphite material. (3) Due to the high flow rate of steam in shell side for a long time, the vortex phenomenon at the bottom of graphite block near the baffle plate is obvious. The long-term eddy current will aggravate the erosion and corrosion of this part and cause the graphite material inside the hole to exfoliate.

According to the failure cause analysis of this failure case, the following three countermeasures are put forward for the safe and stable operation of the porous graphite heat exchanger:

(1) After the graphite block is machined, the actual structure should be analyzed by finite element method. The reinforcing rib should be added in the weak part of the structure strength to reduce the stress concentration. (2) In strict accordance with the design regulations and operation procedures, the material is required to be supplied first and then the steam is supplied. The steam should be heated slowly to avoid high temperature difference stress. (3) Reduce the flow rate of steam erosion on the bottom of the graphite block to reduce steam erosion

References
[1] Xu Li, Li Tao. Application of graphite heat exchanger in phosphoric acid industry [J]. Guangdong chemical industry, 2015, 42 (15): 127-128.
[2] Wu Feng, Zhang canbing. Application of graphite heat exchanger in hydrochloric acid analysis [J]. Chemical management, 2017, 2: 108-109.
[3] Hang Yuhong. Impregnation process and impregnation process evaluation of graphite chemical equipment [J]. Total corrosion control, 2014, 28 (12): 41-43.
[4] Shaheryar, A; Khan, S. Mechanical and thermal properties of hybrid carbon fibre-phenolic matrix composites containing graphene nanoplatelets and graphite powder [J]. Plastics Rubber and Composites, 2017, 46(10): 431.
[5] Jiang Fengyi, Tian Mengkui, Hao Litong. Modification of phenolic resin and its graphite impregnation properties [J]. Progress in chemical industry, 2018, 37 (6): 2316-2322
[6] D. C. Carmichael, W. C. Chard. Dense isotropic graphite fabricated by hot isostatic compaction [M]: Ohio, Battelle Memorial, 2004: 113-114.
[7] The Huu Nguyen; Minh Thanh Vu. Effect of Carbon Nanotubes on the Microstructure and Thermal Property of Phenolic/Graphite Composite [J]. International Journal of Chemical Engineering, 2018(01): 17-19.
[8] Lee, Sang-Min. Changes in the Porosity of Bulk Graphite According to the Viscosity of Resin for Impregnation [J]. Carbon Letters, 2015, 16(2): 132-134.
[9] Lin W, Sunden B. A Performance Analysis of Porous Graphite Foam Heat Exchangers in vehicles [J]. Applied Thermal Engineering, 2013, 50(1): 1201-1210