Application of elastic-plastic analysis method in high pressure heater tubesheet design

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Abstract. The design method of pressure vessel consists of the elastic analysis method and the elastic-plastic analysis method. The design method based on elastic-plastic theory with more complex computation process contributes to lightweight design, and avoids uncertainty of stress classification in the complex structures. Tubesheet is the main part of high pressure heater, which is very thick based on Chinese code GB151 for the design of heat exchangers. Increased tubesheet with large thermal stress are not conducive to manufacture, heat transmission and detection. The application of limit load method and elastic-plastic method in the analysis and design of high pressure heater tube is to provide direction for the lightweight research of tubesheet. It is shown that high stress appears on the inner wall of jointing of tubesheet with the head due to the original tubesheet owning enough rigidity related to thickness, which should be noted in the design. The limit load method and elastoplastic method could be assessed in the plastic collapse assessment after optimizing the thickness of the tube plate by 5% on the basis of the existing rule design. Compared with the limit load method, the elastic-plastic method could obtain higher limit load due to its higher computational precision. On the other hand, the design method of elastic-plastic analysis method is not required to consider the determination of limit load per ASME VIII-2 judged by its convergence. The elastic-plastic analysis method is worth further study, which is helpful to the revision and improvement of relevant standards in China.

1. Introduction
As the problem such as the energy shortage and environmental pollution gets worse, the modern equipment gradually shows the development trend of high parameter, large scale and complication in order to keep between energy saving and environmental protection coordinated. Large pressure vessels consume more materials and make more difficulties, so the light-weight of pressure vessels could effectively reduce resource consumption, which conforms the concept between economic and environmental development. High pressure heater is the important auxiliary engine of generating equipment, and tubesheet is the main part of high pressure heater, which is essential to ensure equipment safety and reduce the cost. With the continuous development of electric power equipment, high pressure heater becomes more and more large, so reasonable design of tubesheet is becoming more and more important. If the design pressure is 40MPa, the thickness of the tube plate is as high as 800mm, which is close to the limit of forging level in China limiting the further development of high-end equipment.

Plastic collapse is a major failure mode of pressure vessel given the assessment criteria in different countries. The design method of pressure vessel could be divided into the elastic analysis method and
the elastic-plastic analysis method. The design method based on elastic-plastic theory with more complex computation process contributes to lightweight design, but avoids uncertainty of stress classification in the complex structures. However, the current analysis design standards on elastoplastic analysis are not introduced in China. Moreover, most relevant technologies, technical data and indicators are from abroad, and the verification analysis and experiments on the specific situation in china are insufficient. It is urgent to carry out engineering application research. In this paper, the application of elastic-plastic analysis method in high pressure heater tubesheet design is studied.

2. Assessment method

The design method based on elastic-plastic theory with more complex computation process contributes to lightweight design, but avoids uncertainty of stress classification in the complex structures[1-3]. The limit load method is novel in that the material parameters and structural parameters are directly obtained to obtain max limit pressure that the structure could suffer. It is based on the gradual loading of the structure from zero. When the load increases to a certain extreme value, structure occurs plastic collapse losing the carrying capacity. Limit load value is the ultimate load of the structure. Limit load analysis belongs to the problem of plastic. Several assumptions need to be introduced[4]: Material conforms to the ideal elastoplasticity; and structure satisfies the small deformation state. Mises yield conditions and related flow criteria are used.

The design methods by analysis based on elastoplastic theory mainly include EN 13445-2002 and ASME VIII-2-2007. There are obvious differences between the two methods, and specific analytical methods including modeling, determining and applying boundary conditions, loading process and post-processing of calculation results, etc., will be processed by the designer based on actual conditions[4-8]. In the process of pressure vessel design based on plastic analysis, the constitutive relation of materials needs to be completely understood. There are two important characteristic quantity: (1) Load capacity (limit load or plastic collapse load), which represents the strength of the material; (2) plastic strain, which represents the characteristic quantity of structural strength. ASME VIII-2 selects the limit load and the plastic collapse load as the evaluation criteria controlling the use criteria of excessive deformation. ASME-VIII-2 is more consistent with the traditional strength design specification, which is similar to the design thought in China. Therefore, this paper focuses on the application of limit load method and elastic-plastic method in the analysis and design of high pressure heater tubesheet.

3. Example

3.1. Initial Condition

The initial design parameters of the high pressure heater tubesheet structure are shown in Table 1. Yield strength and tensile strength of the materials were referenced in GB 150.2 and NB/T 47008, and the material and mechanical properties of the principal components are shown in Table 2. According to ASME VIII-2 appendix 3-D, the material performance curves are generated, as shown in Fig. 1. ASME VIII-2 Part 5(2013 version) is used to prevent the analysis of plastic collapse, focusing on the limit load method and elastic-plastic method. According to [9], the whole tubesheet model is used in the whole analysis process to obtain the more accurate results in a local area. Therefore, the weakening effect of trepanning on tubesheet is not introduced by coefficient method. Perforation pattern with triangle in shell side is selected. The max radius of the perforated region is 906mm. The limit load and elastic-plastic analysis method are used to select an one-fourth finite element model due to the symmetrical structure and loading. In order to further simplify the calculation, the contact model between pipe and tubesheet is set as one part. Part of welding joint is neglected.
Table 1  Initial design parameters of high pressure heater tube

| Parameter                          | Value            |
|-----------------------------------|------------------|
| Design Pressure                   | 40Mpa            |
| Work Stress                       | 32.3 Mpa         |
| Design Temperature                | 330 °C           |
| Tubesheet Thickness               | 465.5 mm         |
| Inlet Temperature of Water Supply | 279.8 °C         |
| Outlet Temperature of Water Supply| 299.6 °C         |
| Perforation Pattern               | triangle         |
| Radius of the Perforated Region   | 906 mm           |

Fig. 1  Stress-strain curves of 13MnNiMoR, 15NiCuMoNb and 20MnMoNb

3.2. Modeling and Analysis

The ideal elastic-plastic material model is adopted in the calculation of the limit load, and the Von Mises yield criterion is adopted. The grid uses Solid186 units including a total of 170674 units and 90,2784 nodes. The finite element model and grid division are illustrated in Fig. 2. It is simulated by ANSYS Workbench on the basis of 3D high pressure heater model. The inner of surfaces of water chamber and tube wall are supplied by three pressures: 1.5P, 2P and 3P (P is design pressure). The surface of tubesheet is supplied by three pressure: 1.5P2, 2P2 and 3P2 (P2 is the equivalent pressure on tubesheet surface). The analysis process consists of three step loads. To ensure the accuracy of simulation, Solid186 (3-D solid element) element is utilized to mesh all the structure, and the mesh size of the model has passed the mesh test. The load stress model is presented in Fig. 2.
The influence of large deformation is considered in the elastic-plastic method, and the material plastic mechanical behavior is subject to the Von Mise yield criterion and the following hardening dynamic criterion. Yield strength and tensile strength of the materials are shown in Table 2, and the mechanical behavior of the materials satisfies the real stress-strain constitutive relation as shown in Fig. 1. Solid186 (3-D solid element) element is utilized to mesh all the structure, and the mesh size of the model has passed the mesh test. The load stress model is shown in Fig. 5. The inner of surfaces of water chamber and tube wall is supplied by four pressures: P, 1.5P, 2P and 3P (P is design pressure). The surface of tubesheet is supplied by four pressures: P2, 1.5P2, 2P2 and 3P2 (P2 is the equivalent pressure on tubesheet surface). The surface of the inlet and outlet pipe is applied by four pressures: P3, 1.5P3, 2.4P3 and 3P3 (the equivalent pressure on inlet and outlet pipe surface). The axial displacement constraint is applied to the end face of the shell, and symmetric constraints are applied to the symmetric surface, and the boundary conditions of the first load step are presented Fig 3.

Table 2 Material parameter

| Component | Materials | Elasticity modulus (MPa) | Poisson's Ratio | Allowable Stress (MPa) | Yield Strength (MPa) |
|-----------|-----------|--------------------------|----------------|------------------------|---------------------|
| Head      | 13MnNiMoR | 1.82x10^5                | 0.3            | 211                    | 380                 |
| Tube Sheet| 20MnMoIV  | 1.82x10^5                | 0.3            | 172                    | 330                 |
| Shell     | Q345R     | 1.82x10^5                | 0.3            | 119                    | 305                 |
| Tube      | SA556 GrC2| 1.82x10^5                | 0.3            | 138                    | /                   |
3.3. Results of limit Load Method

The stress distribution of the high pressure heater in the following positions is larger, as shown in Fig. 3. The limit load of each point using double slope method, is calculated as shown in Table 3.

| Location | Limit load (Mpa) |
|----------|------------------|
| A        | 72               |
| B        | 78               |
| C        | 72               |

The results are shown in Fig. 4. It is demonstrated that the calculation results are convergent under the 2.4 times design pressure, and the whole structure meets the requirements of preventing plastic collapse. It is shown that high stress appears on the inner wall of jointing of tubesheet with the head due to the original tubesheet owning enough rigidity related to thickness, which should be noted in the design. The results of A, B and C are shown in Table 4. In the process of internal pressure, the jointing of tubesheet with the head is discontinuous, and the deformation is larger.

| Location | Limit load (Mpa) |
|----------|------------------|
| A        | 78               |
| B        | 98               |
| C        | 78               |
4. Discussion
The limit load is the load that causes overall structural instability. This point is indicated by the inability to achieve an equilibrium solution for a slight increase in load. If the numerical solutions under the condition of 1.5 times design pressure are convergent, the equipment in service will not occur plastic collapse. It is shown that the thickness of existing structure tubesheet reduced by 5% could still meet the specification requirements in the corresponding design pressure. According to elastic-plastic method of ASME VIII-2 Section 5.2.4, in order to ensure that the overall structure could pass plastic collapse assessment, the numerical calculation should converge under 2.4 times design load. The results of this paper meet the requirements of ASME VIII-2. It is shown that the tubesheet thickness on the basis of the existing rule design optimized by 5% is still guaranteed in the plastic collapse evaluation. Compared with limit load method, elastic-plastic method is more accurate than the limit load method. More importantly, it is not necessary to determine the limit load to determine whether the structure meets the requirements of the plastic collapse assessment. The elastic-plastic method is further studied on the basis of limit load method, and many scholars have called for the revision of relevant standards in China[10-12]. Although elastic-plastic method is used in analysis design increasing difficulty, the security and reliability benefits of some important pressure vessels are much higher than the cost of complexity[4].

5. Conclusions
The elastic-plastic method is a hot spot in the research of pressure vessel analysis design, which could help to promote the revision and improvement of China's standard. In this paper, the results provide some reference for the design-by-analysis of high pressure heater tubesheet. There are some conclusions which could be obtained as below:

1) There are clear differences between ASME VIII-2 and EN 13445 in elastic-plastic analysis. ASME-VIII-2 is more consistent with the traditional strength design specification, which is similar to the design thought in China. Limit load method and elastic-plastic method could be achieved by finite element software.

2) It is shown that high stress appears on the inner wall of jointing of tubesheet with the head due to the original tubesheet owning enough rigidity related to thickness, which should be noted in the design, and the elastic-plastic method is more accurate. It is shown that the tubesheet thickness on the basis of the existing rule design optimized by 5% is still guaranteed in the plastic collapse evaluation.

3) Compared with limit load method, elastic-plastic method is more accurate than the limit load method. More importantly, it does not need to determine the limit load to determine whether the structure meets the requirements of the plastic collapse assessment. Application of elastic-plastic method in high pressure heater tubesheet provides guidance for designers to implement and select.

Acknowledgements
The authors are grateful for the supports provided by the Shanghai leading talent team building special funds and scientific research project of Shanghai municipal bureau of quality and technical supervision.

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