Research on Light-Weight of the High Pressure Heater Tubesheet

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Abstract The tubesheet is the main component of the high pressure heater, and the rationality of its design directly affects the safety and stability of the system. The light-weight of the tubesheet is conducive to resource saving, avoiding large temperature difference stress caused by excessive tubesheet thickness, and further improving parameters under the prior conditions. Therefore, the light-weight of the tubesheet has become the focus of tubesheet design research. It introduced the research of tubesheet light-weight technology from three aspects of the standard, design and material, and summarized the current research status of related literature at home and abroad. There are several problems in theoretical research and engineering application in the classification of tubesheet light-weight, including complex failure mode, experimental verification difficulties, long data accumulation, etc. It provides a direction for the in-depth study of tubesheet light-weight.

1. Introduction
With the shortage of energy and environmental degradation, the equipment is gradually showing a high-parameter, large-scale and complicated development trend in the modern industrial field. The light-weight construction of pressure vessels meets the concept of coordinated development of safety, economy and resource conservation, and has become the development direction of pressure vessels[1]. High-temperature heater is a major auxiliary machine for energy efficiency and emission reduction of power stations[2]. The tubesheet is a key component of the device, which plays a very important role in the safe operation of the device and the cost reduction. With the continuous improvement of the power of large generator sets, the high-addition parameters are also continuously improved, and the thickness of the tubesheet is continuously increased. For example, the design pressure is 40 MPa and the thickness of the tubesheet is as high as 600 mm. The increase of the thickness of the tubesheet not only increases the manufacturing cost of the equipment, but also is not conducive to heat transfer, easily causes large temperature difference stress, and is not conducive to processing and detecting flaw detection, which increases technical difficulty and safety risk, and under the premise of satisfying the strength, tubesheet thickness should be minimized. Moreover, with the continuous improvement of high-added parameters, some tubesheet forgings have exceeded the existing standard range and reached the manufacturing limit, which has become a bottleneck restricting the development of high-end equipment in China. Therefore, there is an urgent need to carry out related research on tubesheet light-weight. This paper mainly discusses and summarizes the light-weight technology of tubesheet of the design standard, the design theory and the material technology progress.
2. Design standard aspects

2.1. Designed by rules
Based on the thin theory, the early tubesheet are represented by the early American TEMA standard, the current German AD standard, and the current Japanese JISB 8243 standard. The tubesheet is simplified into a solid round plate, which introduces empirical correction factors to reflect various factors. Impact, in order to obtain more accurate calculation accuracy than the actual one, which ignores too many factors, neither conforms to the basic theory of elastic mechanics, but deviates from reality. However, because the method is simple and easy to use, it is still used for some specifications and is applied to practice. The current design method of tubesheet strength is mainly based on the theory of porous equivalent solid circular plate on the basis of elasticity. It is represented by British EN standard, American TEMA new standard, French CODAP standard and China GB151 standard, mainly based on the theory of elastic plate shell and combined with the actual situation of each country. The simplified method derived from the basic principle of elastic failure is also an empirical design method, which mainly controls the stress level of the maximum stress distribution area of the structure, leaving enough safety margin when considering the allowable stress\[3\]. A solid circular plate is used instead of the perforated plate, and relevant parameters are added to describe the weakening effect of the tube hole. The concept of "equivalent design pressure" considering pressure, thermal expansion difference and tubesheet boundary constraints is proposed, but it ignores the reinforcing effect of the heat exchange tubes on the tubesheet. Scholars in china have increased the support of heat exchange tubes through theoretical derivation and a large number of engineering practices. The heat exchanger design standards in china are leading foreign standards in some respects. In order to make the simplified model have the same deflection as the actual tube sheet, the minimum strain energy theory is used to describe the weakening effect of the tube hole on the tube sheet, and the elastic modulus and poisson's ratio of the equivalent solid sheet are instead of the equivalent solid\[4,5\]. Since then, the research on the effective elastic constant of the tubesheet has made great progress\[6,7\].

2.2. Design by analysis
The equivalent tubesheet theory is an approximate calculation, and there are always some deviations from the real value. The analysis design method makes up for the deficiency of the equivalent tubesheet theory. With the development of computer technology, the application and promotion of finite element analysis and design methods are promoted. Reduce the thickness of the tubesheet based on the rule design\[8\]. The stress classification method is an early analytical design method. The theoretical basis is derived from the plate and shell theory, but its supporting strength conditions require comprehensive theory, experimental results and engineering experience. Therefore, in the stress classification process, the user is not only required to have a full understanding of the theoretical basis of the method, but also requires the user to clearly understand the load on the container, the detailed structural size and the like. And there is a problem that the design result deviates from the structural failure state and the design result is unsafe for a few structures. Although it could be compensated by engineering experience, it will produce a problem that the design result is too conservative. The elastoplastic nonlinear analysis design method is more complicated in calculation, but the elastoplastic design method can avoid the difficulty of the elastic analysis design method in the classification of complex structural stress, and it is expected to further realize the tube based on the elastic design. The weight of the board. The elastoplastic analysis design method is represented by direct method and elastic method (plastic method, which is obviously superior to stress classification method in many aspects). The elastoplastic analysis design method is closer to the actual bearing of the structure, which become the trend of pressure vessel analysis design development, and has been supported by many scholars. However, the two design methods are not the same, and the differences are obvious. The pressure vessel design and practitioners in china have conducted in-depth research on some basic ideas of the two standard specifications. Elastic-plastic nonlinear finite element analysis design requires analysis software and support from engineering experience and judgment\[33\].
Independent innovation of pressure vessel design specifications must rely on the combination of theory, experiment and engineering\cite{34}. Therefore, it is necessary to study engineering design and actively carry out engineering applications\cite{21,35}.

3. Design theory aspects

3.1. Tubesheet simplification

The extensive application of analytical design in pressure vessel design has facilitated the development of optimized designs. In order to further realize the light-weight design of the tubesheet, it can be realized by improving the calculation accuracy in the analysis design and combining the Matlab and finite element optimization analysis module to optimize the structure or process\cite{9}. The use of the solid model, although the amount of calculation is improved, can improve the calculation accuracy, but it is not conducive to the tight cycle engineering design. To this end, domestic and foreign scholars have studied the porous equivalent solid circular plate model based on elasticity. The perforated plate model mainly considers the weakening effect of the pipe hole, but some studies have shown that the support effect of the heat exchange tube makes the difference between the stress and deflection distribution of the actual tubesheet and the solid plate. The maximum stress position of the tubesheet is related to the area of the non-pipe area, and the deflection The largest position is near the non-pipe area\cite{19}. Two kinds of finite element analysis models of equivalent solid tubesheet and open tube tube of quenching boiler were established by ANSYS software. The results of stress analysis is show that the stress concentration at the hole edge of the open tubesheet is significant and cannot be simplified. Jin Weiya et al\cite{20} compared the traditional model with the solid model, who found that the stress and strain distributions of the two models are basically the same, and the economic model based on the traditional model of elasticity theory is better. It could be seen that model simplification also requires more engineering practice.

3.2. Calculation method

In the analysis design, the main units used for analysis are flat plate units, shell units, solid elements, pipe units and thermal stress units. The selection of suitable units and models helps to improve the calculation accuracy. However, the force of the heat exchanger tubesheet in the actual work is very complicated, including pressure, temperature, fluid phase change and other factors, and it is necessary to comprehensively consider the mixing of various units. The system has studied the different unit combinations of the tubesheet, and found that the solid tubesheet and shell units can be used together to reduce the amount of calculation and obtain the best calculation results. It is found that the tube bundle is simplified to an elastic foundation and several equal-concentric concentric cylindrical shells having the same metal cross-sectional area as the tube bundle have good precision inside the tube-and-tube tube region, which is simplified to actual. The method of the same number of rods has a poor precision, but has good precision outside the tube area of the tubesheet and in the edge area.

3.3. Structural Process Optimization

Structural and process optimization helps to reduce stress concentrations. In the study of double-tube heat exchangers, it is found that increasing the thickness of the tubesheet can significantly improve the stress of the tube sheet, and has no significant influence on the stress of the tube and the stress of the shell. The thickness of the tubesheet could be reduced by using different thicknesses of the inner and outer tubesheet. It is found that the tresca stress value of the structural groove connection mode is at the maximum position, and when the tubesheet is connected with the shell, the rounded transition mode is adopted as much as possible. The stress analysis is carried out by the method of coupling analysis of the sealing plate and the tube sheet. Compared with the separate analysis, the stress safety performance is increased, the stress concentration is also greatly reduced, and only the weld seam and chamfer on the sealing plate appearing stress concentration. The tubesheet is relatively uniform in stress distribution, and the stress concentration is reduced by increasing the chamfering of the opening.
The most likely location of the heat exchanger is the connection between the pipe and the tubesheet and the tubesheet and the shell, and the most likely location of the prestressed heat exchanger is the joint between the tube and the tubesheet\cite{48}.

4. **Materials process aspects**

4.1. **Improve safety factor**

The strength safety factor of a material is a characterization of the reduction of the allowable strength of the material when designing a pressure vessel with consideration of uncertainties related to material properties, design calculation methods, manufacturing inspection, and operational management. The adjustment of the strength safety factor of the material is a systematic project, not simply reducing the thickness. In order to ensure the safety and stability of the adjusted container, various aspects such as material selection, manufacturing process, container structure, material testing, material management, etc. are required. Make adjustments and improvements. Under the premise of ensuring the intrinsic safety of the pressure vessel, the material strength safety factor can be reasonably reduced, and the light-weight design of the tubesheet can be realized. The methods for determining the allowable stress of materials at home and abroad are compared, and the ways to improve the allowable stress of pressure vessel materials in China are discussed\cite{36}. Therefore, the safety factors in the standards at home and abroad are constantly revised and improved. For example, the tensile strength safety factors of ASME conventional design and analysis design are reduced to 3.5 and 2.4 respectively, which is consistent with the safety factor of tensile strength in EN 13445. In the Pressure Vessel Safety Technical Supervision Regulations, the conventional design tensile strength safety factor is adjusted from the original 3.0 to 2.7, and the analytical design tensile strength safety factor is adjusted from 2.7 to 2.4.

4.2. **New materials**

With the continuous improvement of the requirements of service parameters, many new materials for heat exchangers have been developed and used. Low-alloy steel is widely used in tubesheet design and manufacture due to its relatively low cost and high performance, and can meet different working conditions according to needs. Low-alloy high-strength steel achieves a light-weight design to a certain extent due to its higher strength. However, in the application process of low-alloy high-strength steel, it is necessary to consider the influence of welding process, service environment, heat treatment process and other factors, especially the position of the welded joint.

4.3. **New theory**

Tube board safety assessment involves many factors. In addition to strength factors, fatigue is becoming more and more important in pressure vessel design. In the stability analysis process, the classical stability theorem only defines the structural stability to linear elastic behavior, but the plastic stability is classified as unsafe. It is conservative. Under the condition of low cycle fatigue, plastic stability can ensure structural safety. Plastic stability is recognized by some standards. The traditional linear life accumulation method has unsafe factors, while the nonlinear fatigue life evaluation method improves the design accuracy to a certain extent, but puts higher requirements on data reliability. In addition to traditional mechanics\cite{21}, such as fatigue crack propagation theory based on fracture mechanics\cite{23}, probability and statistics theory and damage mechanics\cite{23-25}, life prediction technology is also gradually applied to fatigue design, enriching and perfecting fatigue design theory. Neural network\cite{26}, expert system, fuzzy system\cite{27} and other related technologies in the field of artificial intelligence have also been applied to fatigue designs to solve life prediction problems under complex conditions. The new theory is proposed and applied to improve the prediction accuracy and ensure a reasonable safety margin, but it also puts higher requirements on the designer level and experience.
5. Conclusion

In summary, the light-weight design of the tubesheet is one of the important ways to improve high-end power generation equipment in China. Through the light-weight of the tubesheet, it could further promote the green design and manufacturing, achieve energy saving and emission reduction. At the same time, it could help to enhance the international competitiveness of “Made in China” and promote the updating of relevant standards in China. Although tubesheet light-weight has achieved certain results in terms of standards, design and materials, the rule design still focuses on experience. The new design methods and design theories still need carry out more engineering practice. In particular, there are still many aspects to be improved in the development.

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