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Design and Fatigue Analysis of High Pressure Shell and Plate Heat Exchanger

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Abstract. As a kind of widely used industrial equipment for energy exchange, heat exchanger is widely used in daily life. It is a key equipment for heat recovery and is of great significance for energy saving. In this paper, firstly, the heat transfer characteristics of the heat exchanger were analysed. Then the structure, material and performance parameters of the heat exchanger were analysed for the typical titanium alloy shell and plate heat exchanger, and the heat exchanger was checked by ASPEN software. At last, the fatigue analysis under the pressure of 2MPa was carried out for the heat exchanger, and the life, damage, safety factor and fatigue sensitivity curve of the shell plate were obtained, which provides certain reference basis for the structural design and optimization of the heat exchanger.

1. Introduction

Under the current technology, the effective utilization rate of energy is too low. As much as half of the energy is contained in waste water, which is discharged into the surrounding environment. While generating heat pollution to the earth environment, it also causes great waste of energy. Rational use of heat exchanger can fully recycle and utilize this part of heat for reproduction or derivative industry, which can reduce environmental pollution and strengthen environmental protection, save cost, generate economic benefits and improve energy utilization rate.

2. Numerical analysis

2.1. Analysis of heat transfer intensity

Empirical formula is used to calculate the Nusselt(Nu) number in the shell of heat exchanger. Nu number represents a criterion of the intensity of convection heat transfer, and also represents the ratio of thermal resistance and convection heat transfer resistance at the bottom of laminar flow. This paper uses Kern empirical formula to verify the calculation.

The specific form of Kern empirical formula is as follows:

$$Nu = 0.36\,\mathrm{Re}^{0.55}\,\mathrm{Pr}^{0.33}\left(\frac{\eta_f}{\eta_w}\right)^{0.14} \tag{1}$$

- η is the hydrodynamic viscosity.
- f is to take the average temperature of fluid as the qualitative temperature.
- w is to take the temperature of the pipe wall as the qualitative temperature.

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Since water is used as the heat transfer medium in this paper, and the average temperature of the fluid is not different from the temperature of the pipe wall, and the physical parameters of water change very little, it can be approximately considered that η_f and η_w are equal. Thus Kern empirical formula can be reduced to:

$$Nu = 0.36\,\mathrm{Re}^{0.55}\,\mathrm{Pr}^{0.33} \tag{2}$$

Cross sectional area of shell circulation:

$$S = BD_i(1 - d_0 / t) \tag{3}$$

Shell circumference:

$$C = 2\pi D_i + 2n\pi d_0 \tag{4}$$

Equivalent diameter:

$$d_e = 4S / C \tag{5}$$

Average velocity of fluid over the shell:

$$u = vs / S \tag{6}$$

Shell Reynolds number:

$$\mathrm{Re} = \frac{u d_e \rho}{\eta} \tag{7}$$

2.2. Analysis of heat transfer characteristics

Heat transfer from the heat exchanger:

$$Q = Dc_p(t_1 - t_2)\times 10^3 \tag{8}$$

- D is the mass flow of cooling liquid.
- c_p is the specific heat capacity of liquid.
- t_1 and t_2 are the temperature of liquid inlet and outlet.

The heat transfer area of the heat exchanger:

$$F' = Q / (\Delta t \times K) \tag{9}$$

- Δt is the temperature difference of liquid inlet and outlet.
- K is the heat exchange coefficient.

3. Structural design specification

3.1. Structure of titanium alloy shell plate heat exchanger

All-welded titanium alloy circular plate and shell heat exchanger is composed of shell components, heat exchange plate bundle components, pipe and shell heat exchangers. It is a new heat exchange equipment with advantages of both plate and shell heat exchangers. It has advantages of high heat transfer efficiency, strong pressure and heat resistance, good sealing performance, safety and reliability, and compact structure. The shell side medium is seawater, the plate side fluid is fresh water, and the reverse flow is arranged. The structure of the heat exchanger is shown in the figure below.

The shell and plate heat exchanger is designed with all-welded dismountable integration, which not only retains the high efficiency of the original plate heat exchanger, but also greatly improves the pressure performance of the plate heat exchanger. Achieve design pressure of 2MPa.The heat exchanger core is designed to be dismountable for easy cleaning. Main components of heat exchanger are shown in Table 1.

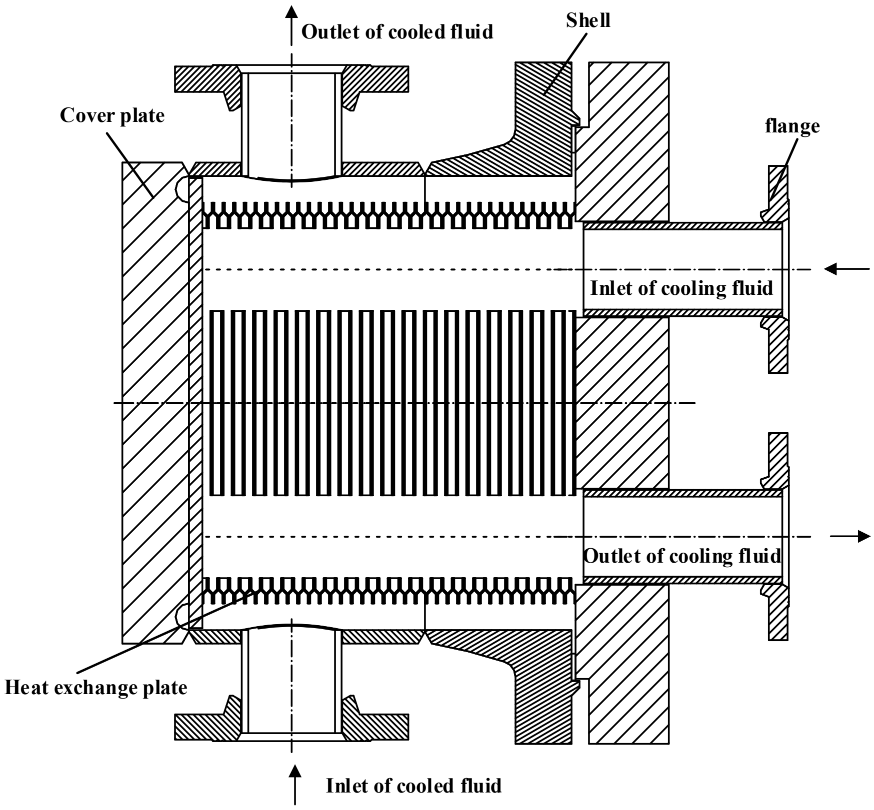

Figure 1. Schematic diagram of heat exchanger structure.

Table 1. Table of component material composition.

Parts	Material type	Material
Heat exchange plate	plates	TA1-A
Cover plate	forge piece	TA2
flange	plates	TA1

The shell and beam of the plate and shell are welded into a whole by titanium alloy. The sheet and sheet are closely packed together, and support each other to form honeycomb network structure. The whole structure is more stable and reliable, and it has the same pressure capacity as the tubular heat exchanger under the enclosure of the shell. The heat exchange plate is made of titanium plate under primary pressure, and the structure is shown in the figure below.

The performance parameters of heat exchanger are as follows:

- Number of sheet plates:70
- Veneer area: 0.07m^2
- Heat transfer area: 4.83 m^2
- Margin: 10%
- Flow rate between seawater plates: 0.47 m/s
- Flow rate between freshwater plates: 0.46m/s
- Number of sheet plates: 70

- Barrel body diameter: 340mm
- Ripple depth: 3mm

Figure 2. Schematic diagram of heat exchange plate structure.

3.2. Simulation model of ASPEN

Based on the related parameters and boundary conditions of heat exchanger, the ASPEN simulation model is established to check the related parameters of heat exchanger.

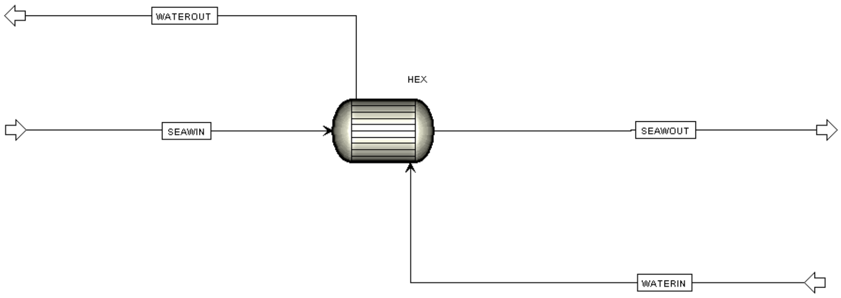

Figure 3. Schematic diagram of simulation model.

Given the sea water side flow is 50t/h, the inlet temperature is 28°C, the fresh water side flow is 50t/h, the outlet temperature is 38 °C, and the total heat transfer is 200kW.

Table 2. Table of component material composition.

Type	Inlet temperature	Outlet temperature	Heat exchange area
The sea side	28 °C	31.69 °C	7.2m^2
Fresh water side	41.43 °C	38 °C	7.2m^2

The simulation results of the heat exchanger show that under the condition of guaranteeing the outlet temperature of fresh water, the required area of the heat exchanger is 4.1m^2. The design area of heat exchanger is 4.83m^2, which meets the use requirements.

4. Fatigue analysis

4.1. Parameter Settings

The material properties of heat exchanger plates are set as shown in the table below.

Table 3. Table of material property.

Type	Numerical value	Type	Numerical value
Material	TA1	Tensile strength (MPa)	402.5
Density (kg/m^3)	4510	Yield strength (MPa)	396.8
Elastic modulus (GPa)	98.5	Heat transfer coefficient (W/(m^2K))	1500

Poisson's ratio	0.34	Linear expansion coefficient (m/K)	8.0×10^{-6}

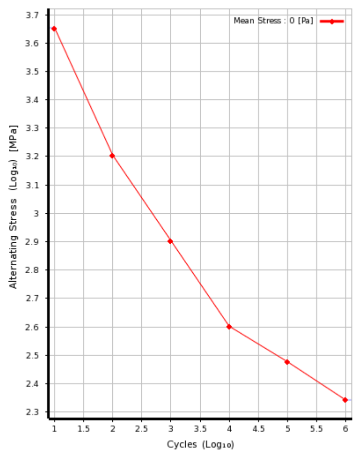

Figure 4. The s-n curve of TA1.

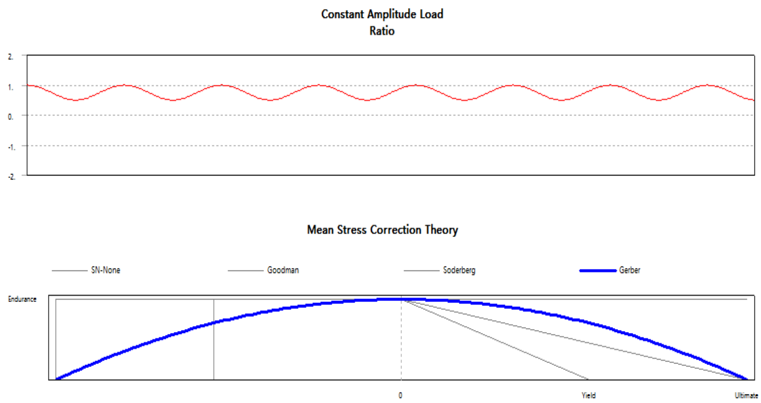

Figure 5. Loading spectrum and Gerber correction theory.

Assuming titanium alloy as ductile material, Gerber's average stress correction theory is adopted.

- Fatigue life design: 3000 times
- The proportion of load spectrum is 0.5

4.2. Static analysis

Static analysis of the heat exchanger plate is carried out. The equivalent stress cloud diagram is shown below.

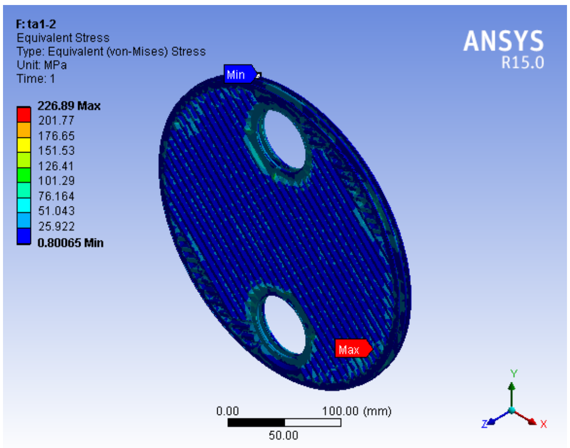

Figure 6. The cloud map of equivalent stress.

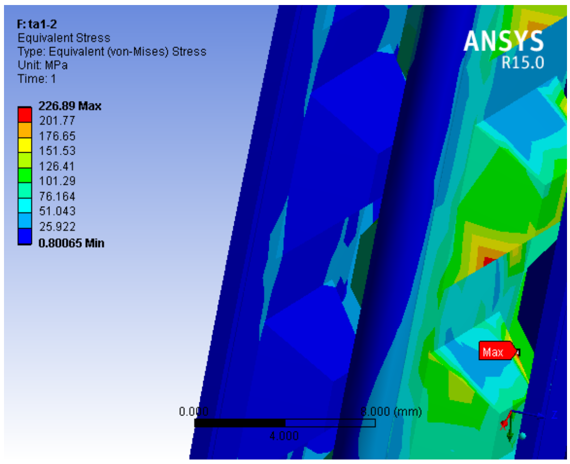

Figure 7. The maximum of equivalent stress.

The maximum stress is 226.89MPa, less than the yield strength. The maximum stress is located on the ridge between two small circular welds at the edge of the middle plate. The greater stress is concentrated around the weld.

As can be seen, the maximum deformation is 0.10919mm, and the maximum deformation is the tooth lines between two small circular welds at the edge of the middle plate. Large deformation is concentrated around the weld. The maximum deformation is small and the deformation control is well.

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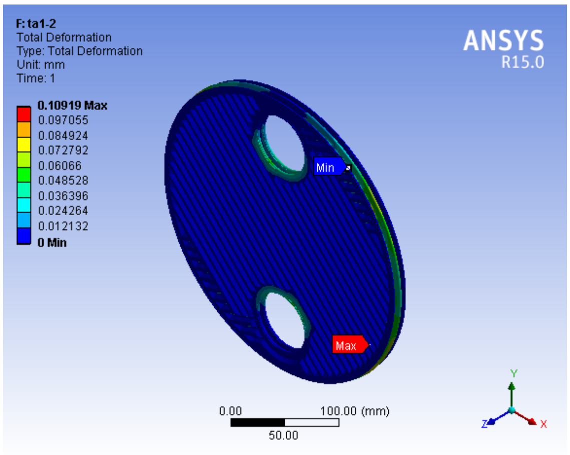

Figure 8. The cloud map of integral deformation distribution.

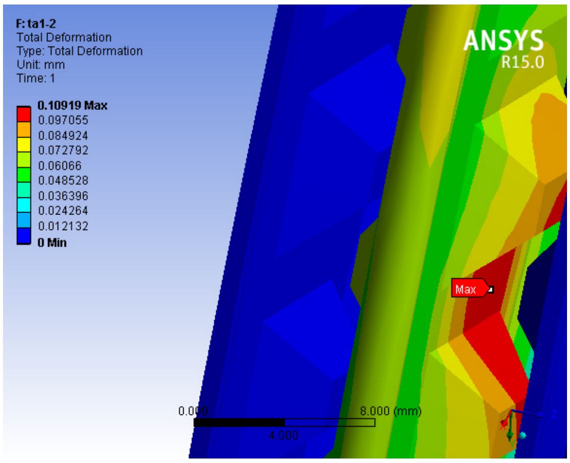

Figure 9. The maximum of integral deformation distribution.

4.3. Fatigue analysis

4.3.1. Life

Life is the number of cycles from fatigue to failure, because the input is the load spectrum, and its value represents the number of cycles that can be cycled in the load spectrum. The maximum life force on the curve of the material is 1e6 cycle times, so the maximum life is 1e6 cycle times. Life chart shows that the fatigue life of all parts of the structure is greater than 3,000 times.

4.3.2. Damage

Damage is the ratio of design life to available life. When the damage value is less than 1, fatigue failure will not occur. When the damage value is greater than 1, fatigue failure occurs. All damage values in the figure are less than 1.

4.3.3. Safety factor

Safety Factor is the ratio of failure stress and design stress of parts and materials. When the Safety Factor is greater than 1, it can meet the design requirements. The safety coefficients in the figure are all greater than 1.

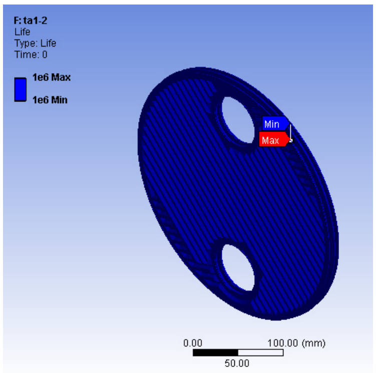

Figure 10. The figure of life.

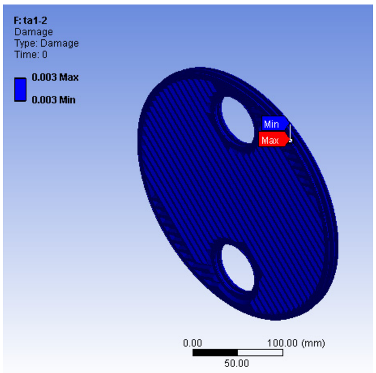

Figure 11. The figure of damage.

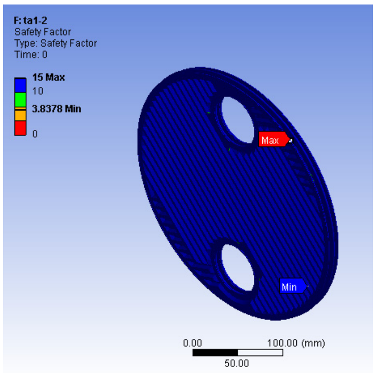

Figure 12. The figure of safety factor.

5. Conclusions

For new type structure of titanium alloy shell plate heat exchanger, statics analysis was carried out on the heat exchanger. The analysis results show that the heat exchanger plate of the maximum equivalent stress value is 226.89 MPa, less than the yield stress of TA1($\sigma_s = 320MPa$).

Based on the static analysis, the fatigue life of the heat exchanger was analysed, and the results of the life, damage, safety factor and fatigue sensitivity curve of the shell plate were obtained, so the stress concentration and fatigue damage prone area of the shell plate were obtained, which provided certain reference basis for the structural design and optimization of the heat exchanger.

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