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RESEARCH ON THE PRESSURE-TEMPERATURE CURVE OF REACTOR PRESSURE VESSEL AND ITS KEY PARAMETERS

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ABSTRACT

Nuclear power plants need to control the pressure and temperature within a certain limit during the process of starting, stopping the stack and other heating and cooling process. That is, the pressure-temperature limit curve (P-T curve) for reactor pressure vessel (RPV) needs to be satisfied. As the reactor reaches its end of life, long-term neutron irradiation will cause the fracture toughness of the reactor pressure vessel (RPV) to decrease. Within the safe operating temperature range of the nuclear power plant, the permissible stress of the RPV determined by the fracture toughness of the material also decreases. In this paper, the fracture safety analysis of a nuclear power plant under the condition of a normal start and stop mode of reactor is carried out. The thermal stress distribution of the pressure vessel is calculated by finite element method, and the limited pressure associated with the system temperature is calculated with fracture mechanics method to generate the pressure - temperature limit curve. The influence of the key parameters such as crack orientation, temperature drop rate, and the neutron irradiation flux on the P-T limit curve was analysed as well.

KEY WORDS: pressure-temperature curve; reactor pressure vessel; crack orientation; temperature rate; neutron irradiation flux

INTRODUCTION

During the operation of the reactor, RPV is subjected to a large amount of neutron radiation for a long time, which causes the fracture toughness of the material in the core zone of the RPV to decrease. Thus, changes in pressure and temperature during the start-up and shutdown of nuclear power plants are more likely to cause brittle fracture of RPV. Therefore, in order to prevent fracture of RPV during the its service period, the US, France, and other countries have imposed restrictions on the pressure-temperature curve of the RPV, thereby ensuring the safe operation of nuclear power plant(Shu G.G, 2006).

ANALYTICAL METHOD

The fracture failure criterion of different standards is based on the I-type crack assumption. Therefore,

$$K_I < K_{IC}(K_{IR}) \tag{1}$$

The appendix ZG of the RCC-M standard gives the form the critical stress intensity factor of the end-of-life material, which involves a reference fracture toughness KIR, as shown follows，

$$K_{IR} = \min\begin{cases} 29.43 + 1.355\exp\left[0.026\left(T - RT_{NDT} + 88.9\right)\right] \\ 195 MPa\sqrt{m} \end{cases} \tag{2}$$

Where T is the temperature at the crack tip (℃); RT_{NDT} is the non-ductile transition temperature of the material, as follows,

$$\Delta RT_{NDT} = \left[22 + 2778\left(P - 0.008\right) + 556(Cu - 0.08)\right]\left(f/10^{19}\right)^{0.5} \tag{3}$$

Where P means the mass percentage of phosphorus. When it is less than 0.008%, P = 0.008; Cu means the mass percentage of copper. When it is less than 0.08%, Cu = 0.08; f is the neutron fluence.

For the solution of the stress intensity factor due to thermal loads, the RCC-M specification gives a semi-analytical formula of the crack stress intensity factor expressed by a function of the fitted polynomial coefficient and the crack depth a and the wall thickness t,

$$K_I(a)=\sum_{j=0}^{4}K_{Ij}(a)=\sum_{j=0}^{4}\left(\sqrt{\pi a}\sigma_j i_j\left(\frac{a}{t}\right)^j\right) \tag{5}$$

$$\sigma(x)=\sigma_0+\sigma_1\left(\frac{x}{t}\right)+\sigma_2\left(\frac{x}{t}\right)^2+\sigma_3\left(\frac{x}{t}\right)^3+\sigma_4\left(\frac{x}{t}\right)^4 \tag{6}$$

Where x is the coordinate of each point on the normal stress fitting path.

FINITE ELEMENT ANALYSIS

Finite element model

In this paper, the finite element method is used to obtain the thermal stress distribution of RPV under thermal loads. Taking a pressurized water reactor nuclear power plant as the object, it is assumed that there is axial semi-elliptical defects on the inner surface the RPV wall, as shown in Fig.1. The crack depth a=50 mm, and the crack length 2c=6a=300 mm. The finite element model is shown Fig. 2.

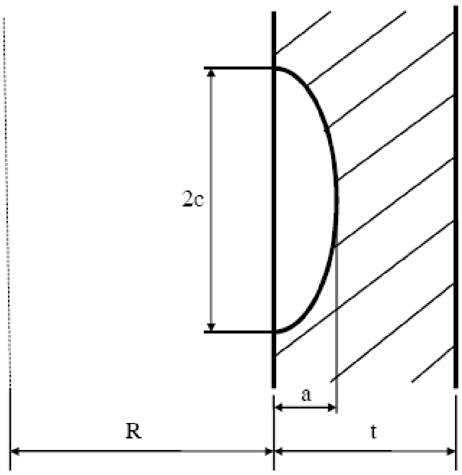

Fig. 1 Axial crack indication

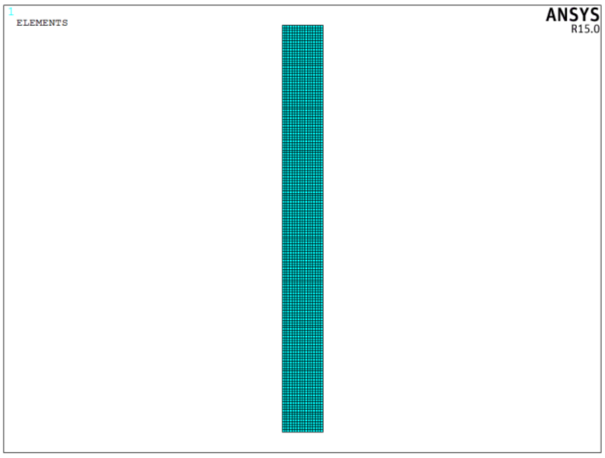

Fig.2 Finite element model

Material Properties

The material of the vessel is low-alloy ferritic steel 16MND5. The thermal stress analysis uses the elastic modulus, linear expansion coefficient, specific heat and heat transfer coefficient of the material at 20-350 ℃. In addition, the Poisson's ratio and density of the material at different temperatures are constant, Poisson's ratio is 0.3, and density is 7900kg/m^3. According to the results provided by the physical calculation of the reactor, the neutron fluence of the inner surface of the pressure vessel after the unit operated for 40 years was 7.12×10^{19} n/cm^2. The initial non-ductile transition temperature of the pressure vessel material was -27℃, and the main chemical element mass percentage was: P (%) = 0.006, and Cu (%) = 0.05.

Load condition

The normal start-up and shutdown rate of the reactor unit is not greater than 55°C/h, so the calculation is based on a cooling rate of 55 °C/h. The temperature variation range is from 310 °C to 31°C.

Finite Element Results

The thermal analysis was completed using the PLANE55 unit, while the structural analysis was completed using the PLANE182 unit. Figure 3 shows the temperature variation over time at different positions of the container wall (including inner wall, crack tip, and outer wall) obtained from thermal analysis. It can be seen that as time increases, the temperature decreases, and temperature differences occur at different positions on the vessel wall. Figure 4 shows the distribution of circumferential stress along the wall thickness at different times obtained from structural analysis. It can be seen that during the cooling process, the stress on the vessel wall gradually transitions from tensile stress to compressive stress from the inner wall to the outer wall.

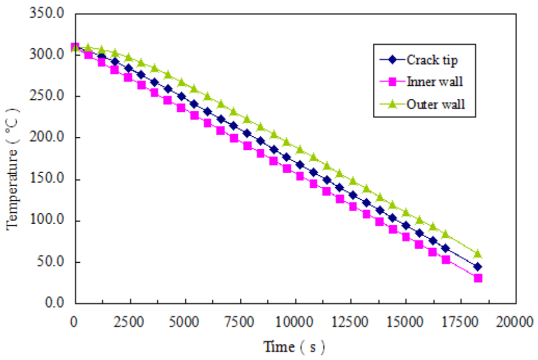

Fig.3 Temperature variation vs time

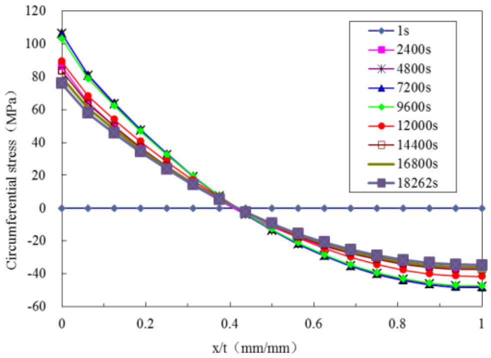

Fig.4 circumferential stress along wall thickness

Figure 5 shows the P-T limit curve calculated for the nuclear unit after 40 years of operation at a cooling rate of 55℃/h. The P-T curve of the nuclear power plant unit under operating modes (including refueling shutdown mode, maintenance shutdown mode, cooling normal shutdown mode, reactor power operation mode, etc.) is shown in Figure 5. It can be seen that the P-T curves of the normal operating mode of the unit have not exceeded the P-T limit curve, so the verification results meet the requirements.

To study the influence of crack orientation, it is assumed that there is a circumferential semi elliptical crack on the inner wall of the container, with a crack depth of a=t/4=50mm and a crack length of 2c=300mm, as shown in Figure 6. Figure 7 shows the P-T curve results under different crack orientations (circumferential and axial). It can be seen that under the same conditions, the P-T curve of circumferential cracks is higher than that of axial cracks. At the same temperature, the limiting pressure of circumferential cracks is about twice that of axial cracks, indicating that axial cracks have stricter requirements for limiting pressure.

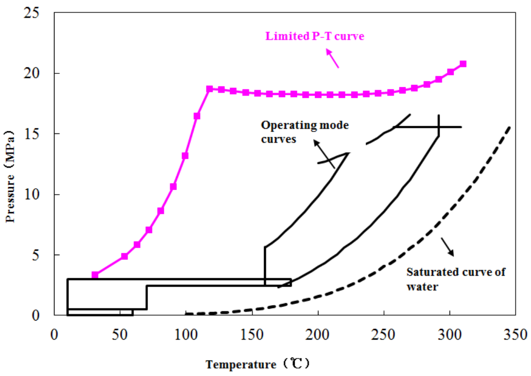

Fig.5 P-T curve verification results

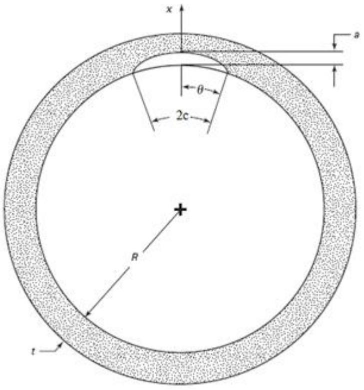

Fig.6 Schematic diagram of circumferential cracks

To investigate the effect of temperature change rate, assume a cooling rate of 28 ℃/h for calculation. Figure 8 shows the P-T curve results for different cooling rates (55 ℃/h and 28 ℃/h). It can be seen from the figure that the influence of thermal load on the P-T curve is not significant under the conditions of this case.

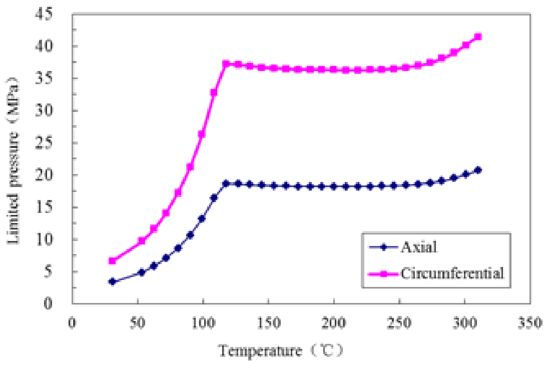

Fig.7 P-T curves under different crack orientations

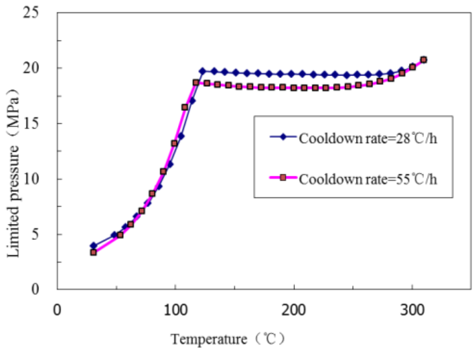

Fig.8 P-T curves at different cooling rates

To study the influence of material degradation, the P-T restriction curves were calculated for the neutron fluence equal to 1 × 10^{19}n/cm^2, 3 × 10^{19} n/cm^2, and 5 × 10^{19} n/cm^2 , and the corresponding adjusted non ductile transition temperatures were obtained as -5℃, 11.11℃, and 22.19℃, respectively. The calculated P-T curve results are shown in Figure 9. As shown in the figure, as the operating cycle of the reactor increases, the operational space of the P-T curve gradually decreases, indicating that the influence of neutron irradiation flux on the P-T curve is very significant.

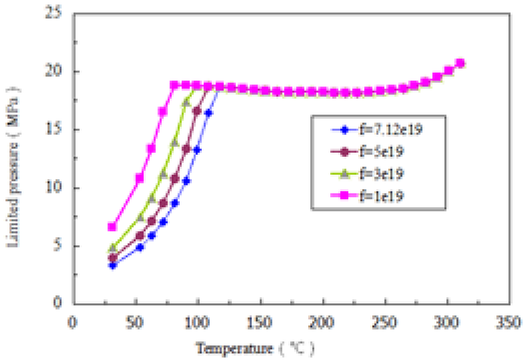

Fig.9 P-T curves under different neutron fluence

CONCLUSIONS

The temperature and pressure of RPV must satisfy the limits specified in the P-T limit curve during normal start-up, shutdown, and hydrostatic testing. This paper focuses on the analysis method of P-T limit curve and its key influence parameters. The main conclusions are as follows:
1) the crack orientation has a great influence on the P-T curve. Under the same conditions, the axial cracks has more stringent requirements than the circumferential crack;
2) the influence of cooling rate on P-T curve is not particularly significant;
3) the neutron flux has a great influence on the results, that is, the P-T curve is more stringent with the increase of reactor operating time;
4) when the operating temperature is low, there is little difference between the results of the finite element method and the convenient formula method. In a word, the factors affect the different stages of P-T curve, and the specific application should be considered in combination with the actual working load conditions.

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