Finite element analysis of temperature field of nuclear fuel cladding tube

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Abstract. In this paper, the finite element software ANSYS is used to analyse the influence of the eccentricity of nuclear fuel pellet on the temperature field of the cladding tube. Furthermore, transient heat conduction analysis of a single fuel rod during a loss of coolant accident is carried out. It can be found that the pellet bias has little effect on the temperature difference between the inner and outer walls of cladding tube, but it has a great influence on the temperature of the pellet center. The results obtained by transient analysis show that the cladding tube will melt within 738 seconds in the loss of coolant accident.

1. Introduction
Since the Fukushima nuclear power plant leakage accident, the international community has paid more and more attention to the safety problems of commercial nuclear power plants. At the same time, with the increasing number of nuclear power plants, people also concerned about nuclear safety [1,2]. In the design of nuclear power plant, it is necessary to consider some unexpected conditions during the operation of nuclear power plant, so as to design relevant safety barriers. Nuclear fuel cladding tube is the first barrier to prevent nuclear fuel leakage, whose integrity and reliability are closely related to the safety operation of nuclear power plant. It works in high temperature, high pressure and high radiation environment, so the requirements for cladding tube materials are relatively high. Now the cladding tube material used in major nuclear power plants is Zr-4 alloy. The prediction and evaluation of behavior of fuel rods (including cladding tubes) is an extremely important task in the design of nuclear power plants. However, the cost of using experimental method is relatively high, the operation is also very complex and time-consuming. Thus, the finite element method [3-5] is more general and effective method to analyze the temperature field of the cladding tube.

Considering the relative position of uranium dioxide pellet in the Zr-4 alloy cladding tube, the gap between the pellet and the inner surface of the cladding tube changes, which affects the temperature change of the Zr-4 alloy cladding tube. The distance between the pellet center and the cladding tube center is called offset distance, and the eccentricity is calculated to study the influence of different eccentricity on the temperature of the cladding tube.

In this paper, ANSYS software is used to simulate the temperature field of cladding tube with different eccentricity in the steady state. The temperature changes shown in the simulation results are corresponding to different pellets eccentricity, and the influence of different eccentricity on the temperature field is studied. At the same time, transient heat conduction analysis of a single fuel rod
during a loss of coolant accident is considered in this paper. These simulation results have some reference significance for the design of reactor.

2. **Establishment of finite element model**

2.1. *Establishment of geometric model*

![Figure 1. Geometric model of fuel rod](image)

The overall length of fuel rod is 15mm and chamfer is not considered in this paper. The outer diameter of the cladding tube is Φ9.50mm. The wall thickness is 0.57mm. The diameter of uranium dioxide pellet is Φ8.19mm as shown in Figure 1. The gap between the cladding tube and the pellet is filled with helium with pressure of 2.0MPa.

2.2. *Material parameter*

Thermal conductivity of pellets $k_1$ [6]

$$k_1 = \frac{1}{0.0375 + 2.1658 \times 10^{-3} T} + \frac{4.715 \times 10^9}{T^2} \exp \left( -\frac{16361}{T} \right)$$  \hspace{1cm} (1)

Thermal conductivity of cladding tube $k_2$ [7]

$$k_2 = 7.51 + 2.09 \times 10^{-2} T - 1.45 \times 10^{-5} T^2 + 7.67 \times 10^{-9} T^3$$  \hspace{1cm} (2)

Thermal conductivity of Helium $k_3$ [8]

$$k_3 = 0.0468 + 3.81 \times 10^{-4} T - 6.79 \times 10^{-8} T^2$$  \hspace{1cm} (3)

The unit of the above thermal conductivity is W/mK. The fuel rod line power is 186w/cm. The convective heat transfer coefficient between the cladding tube and the coolant is 20000 $W/ m^2 K$. The coolant temperature is 310°C.

3. **Verification of mesh convergence**

| Table 1. Results obtained by different meshes |
|---------------------------------------------|
| Mesh type | Mesh 1 | Mesh 2 | Mesh 3 | Analytical solution |
|-----------------|--------|--------|--------|---------------------|
| Number of nodes | 25079  | 59058  | 1349892 | /                   |
| Number of elements | 8428   | 16933  | 323716 | /                   |
| Temperature of pellet center °C | 916.73 | 916.45 | 919.93 | 923.64          |
| Temperature of inner wall of cladding °C | 360.07 | 358.93 | 359.35 | 357.53          |
| Temperature of outer wall of cladding °C | 337.12 | 337.08 | 336.93 | 336.95          |
According to the principle of finite element method [9, 10], a fine mesh leads to accurate numerical results. Therefore, in the finite element analysis, it is necessary to verify the convergence of the mesh. The mesh density from small to large is shown in Figure 2.

In this paper, the results of the temperature of the pellet center and the inner and outer wall of the cladding tube obtained by using the above three kinds of meshes are shown in Table 1. The maximum error between the simulation results and the analytical solution is less than 0.79%, which proves that the above grids have good convergence.

### 4. Temperature field of pellet and cladding tube with different eccentricity

The relative position of the pellet in the cladding tube will be different, which will lead to the change of the temperature distribution of the pellet and the cladding tube. The concentric position of cladding tube and pellet as eccentricity $e = 0$. When the pellet center is on the left side of cladding center, the eccentricity is negative. The limit state is that the pellet surface contacts the left inner surface of cladding, and $e$ is - 1. When $e = 1$, the pellet surface contacts the right inner surface of cladding. Table 2 presents the temperature of the key point with different eccentricity. $Tc$ is the temperature of pellet center. $T_{left1}$ represents inner wall temperature of left cladding. $T_{left2}$ denotes outer wall temperature of left cladding. $T_{right1}$ and $T_{right2}$ are inner wall and outer wall temperature of right cladding, respectively.

Radial temperature distribution of different eccentricity is shown in Figure 3. It can be seen that the temperature change trend of pellet is opposite to the offset direction of pellet, but the influence on the temperature distribution of cladding is consistent with the offset direction of pellet. From the thermometers of pellets and cladding with different eccentricities, we can see that the temperature of pellets is lower than that of concentric state, and the influence is greater. The temperature of inner and outer wall of cladding tube on the same side is also affected, but the influence is not significant. The temperature of cladding near the pellets is higher, but it will not affect the temperature difference of inner and outer wall of cladding tube on the same side, which is about 20 °C.

### Table 2. Key point temperature under different eccentricity

| Numble     | $e = 0$ | $e = 0.4$ | $e = 0.7$ | $e = 1$ | $e = -1$ | $e = -0.4$ | $e = -0.7$ |
|------------|---------|-----------|-----------|---------|-----------|------------|------------|
| $T_{c}/°C$ | 919.93  | 819.68    | 894.24    | 895.17  | 896.68    | 820.12     | 894.68     |
| $T_{left1}/°C$ | 359.35  | 349.85    | 351.34    | 349.02  | 367.16    | 360.4      | 367.46     |
| $T_{left2}/°C$ | 336.19  | 332.93    | 333.78    | 332.51  | 341.79    | 339.01     | 343.18     |
| $T_{right1}/°C$ | 357.06  | 360.6     | 367.26    | 367.51  | 350.75    | 351.5      | 353.1      |
| $T_{right2}/°C$ | 336.93  | 339.01    | 343.19    | 341.79  | 332.56    | 332.98     | 333.81     |
5. Transient heat conduction analysis of single fuel rod in a loss of coolant accident

Nuclear safety is now the most important issue, and many problems may cause a large nuclear accident. As the first safety barrier of reactor, the reliability of cladding tube is related to the safety of the whole nuclear power plant. The melting point of Zr-4 alloy is 1758 °C. The temperature of the cladding tube will rise to its melting point when a single fuel rod is in a loss of coolant accident. The result obtained by transient heat conduction analysis shows that the temperature of cladding tube rises to the melting point at 738s as shown in Figure 4.
6. Conclusion

Finite element software ANSYS is used to analyze the influence of the eccentricity of nuclear fuel pellet on the temperature field of the cladding tube. It can be found that the pellet bias will affect the temperature of the pellet center, and the change direction of the temperature field is opposite to the offset direction. The influence on the temperature change of cladding tube is the same as that of the pellet bias direction, and has little effect on the temperature difference between the inner and outer walls of cladding tube, but it has a great influence on the temperature change of the pellet center. Therefore, we should pay more attention to the offset of pellets and the change of relative gap between them. At the same time, transient heat conduction analysis of a single fuel rod during a loss of coolant accident is carried out. It can be seen that it will take about 738s to reached the melting point of cladding tube. The results of transient analysis for fuel rods can only be used as a reference because the influence of other fuel rods is not considered.

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