

# Numerical Simulation Research of the Quenching and Tempering Temperature Filed in Thick Nuclear Power Forgings of 18MnMoNi Steel

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**Abstract.** Quenching and tempering is an important step in the production for large forgings of nuclear power. Combined with the necessary test, the numerical simulation of quenching and tempering can help us to decide the heat treatment methods and process parameters. We simulated the quenching and tempering process of 300mm-level forgings with the finite element software. By compared the simulated results with the actual measured data, the accuracy of numerical simulation should be improved.

## 1. Introduction

Nuclear energy is clean and efficient, and is one of the main ways to solve our energy supply contradictions in the future [1]. In the past few decades, nuclear power technology has been developed rapidly, and the types of reactors have been upgraded from the second generation to the three generation of AP1000. China has designed and built new types of reactors, such as HPR1000 and CAP1400. With the upgrading of the type of reactor, the reactor will develop to be large scale. With the expansion of the nuclear installed capacity, the thickness and size of nuclear power forgings will also increase, which will lead to a decline in forging cooling capacity, thus affecting the product performance stability. This will brings new challenges to the manufacturing technology of large castings and forgings. Quenching and tempering (high temperature quenching + tempering) is an important step in the production for large forgings of nuclear power, such as nuclear pressure vessel and steam generator. Large forgings of nuclear power have high quality requirements in strength and toughness, therefore building the database of numerical simulation of the quenching and tempering temperature filed for nuclear power products is very important. Although the heat treatment process simulation technology for large forgings is not very mature, but combining it with necessary tests can become an auxiliary decision making tool for the quenching method and technological parameters.

In the whole process of quenching and tempering, the cooling after quenching (decide quenching structure) and the temperature rising during tempering (decide tempering effect) are two key processes. We simulated the quenching and tempering process of 300mm-level forgings of 18MnMoNi Steel used in steam generator with the finite element software ABAQUS. By comparing the simulated results with the actual measured data, we improved the accuracy of numerical simulation and got the approximate accurate temperature field.



## 2. Establishment of the finite element model

### 2.1. Heat conduction equations

We can use Fourier heat conduction equation and boundary conditions which reflect the interaction between forgings and the environment to describe the heat transfer phenomenon of forgings during cooling. If the physical parameter  $\rho$ ,  $C_p$  and  $\lambda$  of large forgings are isotropic in x, y, z axis, and then the heat conduction equation in rectangular coordinate system are as follows:

$$\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q' = \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

$\lambda$  —heat conductivity of material [W/ (m·K)];

$q'$  —heat flux of inner heat source [W/m<sup>2</sup>];

$\rho$  —material density [kg/m<sup>3</sup>];

$C_p$  —specific heat at constant pressure [J/ (kg·K)];

$T$  —temperature [K];

$t$  —time [s].

The suitable initial conditions:

$$T(x, y, z, t)|_{t=0} = T_{\text{initial}} \quad (2)$$

$T_{\text{initial}}$  —Initial temperature of forgings.

Convection and radiation heat exchange boundary are most commonly used in large forgings cooling process, it can be described using the third boundary condition:

$$-\lambda \frac{\partial T}{\partial n} \Big|_{\Gamma} = H(T_s - T_f) \quad (3)$$

$H$  —Heat transfer coefficient [W/ (m<sup>2</sup>·K)];

$\Gamma$  —Convective heat transfer boundary;

$\frac{\partial T}{\partial n}$  —Longitudinal temperature gradient;

$T_s$  —surface temperature [K];

$T_f$  —medium temperature [K].

### 2.2. Finite element model

Using the finite element software ABAQUS to simulate the quenching and tempering process of 300mm-level forgings of 18MnMoNi Steel used in steam generator. Forging size is 300 (wall thickness) x 270 x 2980. In accordance with the requirements of nuclear power products, distance from the general performance testing area of nuclear forgings to each heat treatment end must equal a wall thickness  $T$  at least, so the test areas of the general test plate forgings are welded with insulation blocks. The area where the performance sample is taken is 1/4 of the thickness direction of the performance detection area. The actual test plate forgings of steam generator are shown in figure 1. The area where we want to model the simulated temperature field is 1/4 of the thickness of the performance detection zone shown with the dotted line in Figure 1. Quenching temperature is 890°C, and tempering insulation temperature is 640°C.

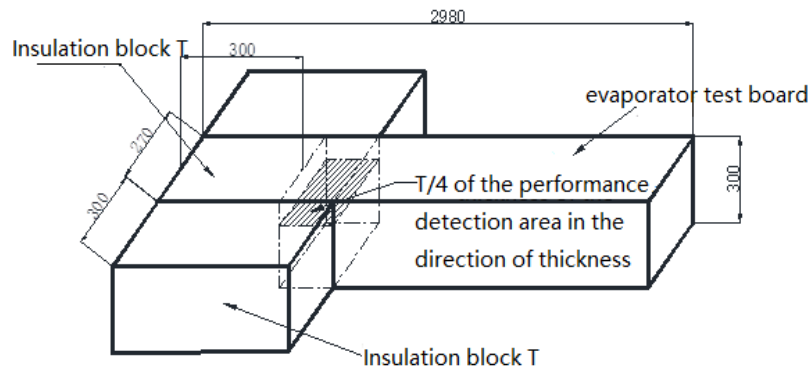


**Figure 1.** Actual test plate forgings of steam generator

We established a finite element geometric model, and the model is shown in Figure 2. In the end, the model has a total of 22,452 units and 95,421 nodes. The simulation program uses the constitutive model UMAT to edit the thermal properties of 18MnNiMo steel for 300mm temperature test specimens. The specific thermal parameters are shown in Table 1. The thermal parameter changes with temperature. When the temperature field is simulated, the ABAQUS software automatically performs linear interpolation fitting on the parameters between the two temperature points.

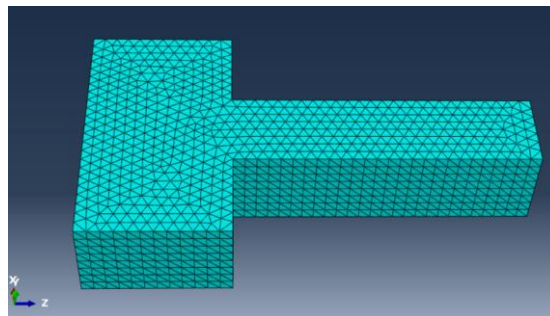


**Figure 2.** Finite element model of 300mm thickness test plate forgings

**Table 1.** Thermal parameters used in the simulation

| Temperature/°C | Thermal Conductivity W/m.K | Specific heat capacity J/Kg.K | Density Kg/m3 |
|----------------|----------------------------|-------------------------------|---------------|
| 50             | 41.29                      | 461                           | 7850          |
| 100            | 41.7                       | 481                           | 7834          |
| 150            | 41.82                      | 500                           | 7819          |
| 200            | 41.64                      | 520                           | 7803          |
| 250            | 41.21                      | 541                           | 7787          |
| 300            | 40.54                      | 564                           | 7771          |
| 350            | 39.67                      | 590                           | 7754          |
| 400            | 38.65                      | 619                           | 7736          |
| 450            | 37.53                      | 652                           | 7719          |
| 500            | 36.35                      | 689                           | 7701          |
| 550            | 31.69                      | 494                           | 7708          |
| 600            | 23.63                      | 566                           | 7771          |
| 650            | 24.24                      | 571                           | 7743          |
| 700            | 24.85                      | 578                           | 7715          |
| 750            | 25.47                      | 586                           | 7688          |
| 800            | 26.08                      | 593                           | 7660          |
| 850            | 26.7                       | 601                           | 7633          |
| 900            | 27.19                      | 607                           | 7611          |

### 3. Quenching cooling temperature field simulation

#### 3.1. Quenched surface heat transfer coefficient

How to calculate the surface heat transfer coefficient  $H$  value is the key to accurately simulate the temperature field of large forgings. During the quenching process of large forgings, the surface heat transfer has to undergo three stages of different mechanisms [2]: membrane boiling, nuclear boiling and convective heat transfer stage, and the corresponding heat transfer coefficient ranges are also different. The surface heat transfer coefficient of the film boiling stage is the smallest, because the surface of the work piece will form a vapor film separating the surface of the work piece from the quenching medium after the quenching starts. At this time, the cooling of the work piece is mainly realized by the heat conduction of radiation and steam, so the thermal coefficient is small. When the vapor film breaks, the quenching medium is in direct contact with the work piece, which generates strong boiling, requires a large amount of latent heat of vaporization, and has the fastest cooling rate and the largest heat transfer coefficient. When the temperature of the surface of the quenched work piece falls below the boiling temperature of the quenching medium, the boiling stops and the convection cooling phase begins, at which time the cooling rate becomes smaller. Therefore, the heat transfer coefficient is usually not a fixed value. However, when quenching large forgings, the steam film will be destroyed by blasting, circulation, spray quenching, etc. and the film boiling stage will be shortened or even eliminated. Therefore, it can be approximated that the surface heat transfer coefficient  $H$  is a constant value in a steady state for most of the time. According to the data given in literature [2], the stable heat transfer coefficient of water is about 2324W/m<sup>2</sup>·K. This coefficient has been applied to the finite element quenching simulation process for many times.

If the heat transfer coefficient is considered to be a change value, then the heat transfer coefficient  $H$ , that is, the anti-heat transfer method, should be reversed by the actual temperature measurement curve. In this paper, the surface heat transfer coefficient  $H$  is calculated by the point difference decomposition inverse heat conduction method on both sides of the near surface. The advantage of this method is that it is simple and intuitive, and there is no non-convergence. The disadvantage is that the accuracy is not high and it is easy to produce errors. A schematic diagram of the calculation of the point difference decomposition method on both sides of the near surface is shown in Fig. 3 [3]. In this way, the third type of boundary condition formula 3 can be transformed into the formula 4:

$$H = -\frac{q}{T_s - T_f}$$

$$T_w = T_1^N - \left(\frac{x_1}{x_2}\right)\left(\frac{\lambda_b}{\lambda_a}\right)\Delta T^N + \frac{x_1(x_1 + x_2)}{4}\left(\frac{1}{a_1}\right)\left(\frac{\lambda_b}{\lambda_a}\right)\frac{T_1^{N+1} - T_1^{N-1}}{\Delta t} \quad (4)$$

$$q = \lambda_w \left[ \left(\frac{x_1}{x_2}\right)\frac{1}{x_1 + x_2}\Delta T^N - \left(\frac{1}{x_1} + \frac{1}{x_1 + x_2}\right)(T_1^N - T_w) \right]$$

$\lambda_a, \lambda_b$ ——Thermal conductivity of material at temperature measuring point a and b [W/ (m·K)]

$T_w$ ——Surface temperature at time n

$q$ ——Surface heat flux at time

$\Delta t$ ——Time step

$T_1^N, T_1^{N+1}, T_1^{N-1}$ ——Instantaneous temperature of point a at time n, n+ $\Delta t$ , n- $\Delta t$

$\Delta T^N$ ——Absolute value of temperature difference between a and b at time n

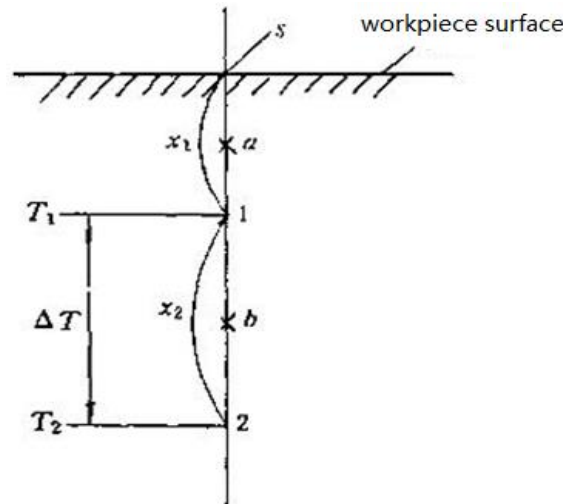


**Figure 3.** Schematic diagram of point difference decomposition method calculation on both sides of the near surface

The temperature curve measured by the two-point method shown in Fig. 3 is brought into the calculation formula (4), and the calculation result of the surface heat transfer coefficient of the actual 300mm-level forgings is obtained, as shown in Fig. 4.

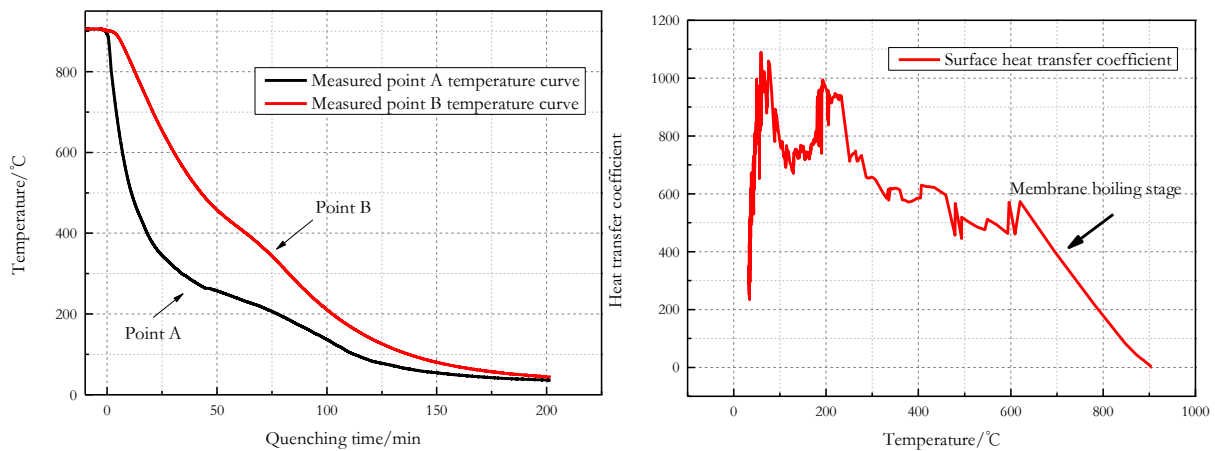


**Figure 4.** Surface heat transfer coefficient calculation result

### 3.2. Calculation of latent heat of phase change

The latent heat is absorbed or released when a tissue transformation occurs during heat treatment. There is no concept of latent heat of phase change in ABAQUS simulation software, so you need to define it yourself. In the simulation calculation, there are usually three methods for treating latent heat [2], namely the equivalent heat method (temperature rise method), the equivalent hot melt method and the specific enthalpy method. Taking the equivalent hot melt method as an example, the influence of the latent heat of phase change on the temperature field is converted into an equivalent hot melt, and the change of latent heat is reflected by the change of hot melt. The formula for equivalent hot melt can be obtained by formula (1):

$$c_{eff} = c_p - L \frac{\partial V}{\partial T} \approx c_p - L \frac{\Delta V}{\Delta T} = c_p + \left| L \frac{\Delta V}{\Delta T} \right| \quad (5)$$

$\Delta V$  — Incremental change in organization within  $\Delta t$

$|\Delta T|$  — Increment in temperature change within  $\Delta t$

$L$  — Latent heat

However, the simulation calculation process for the amount of change in the organization is extremely complicated. For the diffusion type phase transition, the tissue simulation is carried out according to the continuous transformation curve, that is, the CCT curve. Firstly, the CCT continuous cooling process is transformed into the TTT isothermal transformation process according to the Scheil superposition principle (the superposition principle of the incubation period) [4]. The ferrite, pearlite and bainite phase transitions are defined for each node or element in the finite element model based on the incubation period superposition criteria. Thereafter, the amount of transformation of ferrite, pearlite, and bainite is obtained according to the diffusion type isothermal transformation formula [5], as shown in the formula (6). For the martensitic transformation with non-diffusion, the amount of transformation is obtained according to the K-M formula [6], as shown in the formula (7).

$$V = 1 - \exp(-bt^n) \quad (6)$$

$$V = 1 - \exp[-a(M_s - T)] \quad (7)$$

$V$  — Transformation

$n, b, a$  — Constant calculated from the TTT plot

$t$  — transition time

$M_s$  — Martensite transition point

### 3.3. Quenching cooling temperature field simulation results

The quenching cooling temperature field simulated by the fixed heat transfer coefficient  $H$  (2324W/m<sup>2</sup>·K) and the dynamic heat transfer coefficient (Fig. 4) is shown in Fig. 5 and Fig. 6 respectively. The simulated cooling temperature curve of the 1/4 wall thickness of the sample detection area (shaded position in Fig. 1) was compared with the measured cooling temperature curve of the forging piece, as shown in Fig. 7. It can be seen that, compared with the actual temperature measurement curve, the heat transfer coefficient calculated by the point difference decomposition anti-heat transfer method on both sides of the near surface has high accuracy. Compared with the measured curve, the deviation of the average cooling rate of the high temperature section above 400°C is less than 1°C. The cooling rate simulated by the fixed heat transfer coefficient is too fast, which indicates that during the actual quenching process of our large forgings, there is still a film boiling stage.

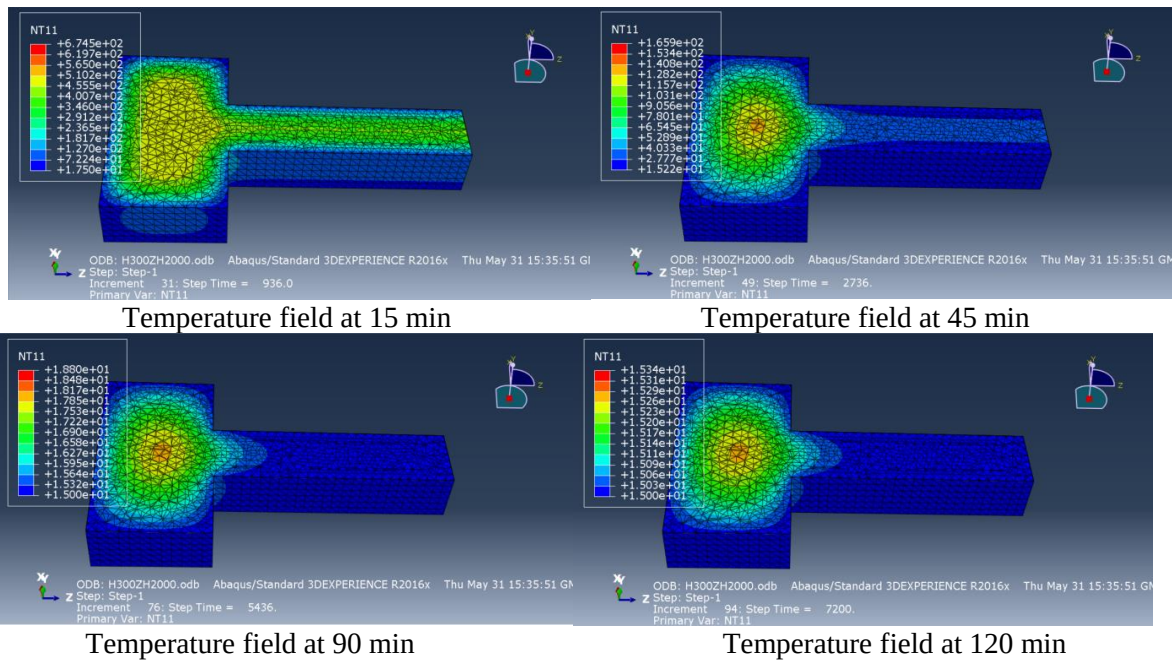


**Figure 5.** Simulated temperature field with fixed heat transfer coefficient

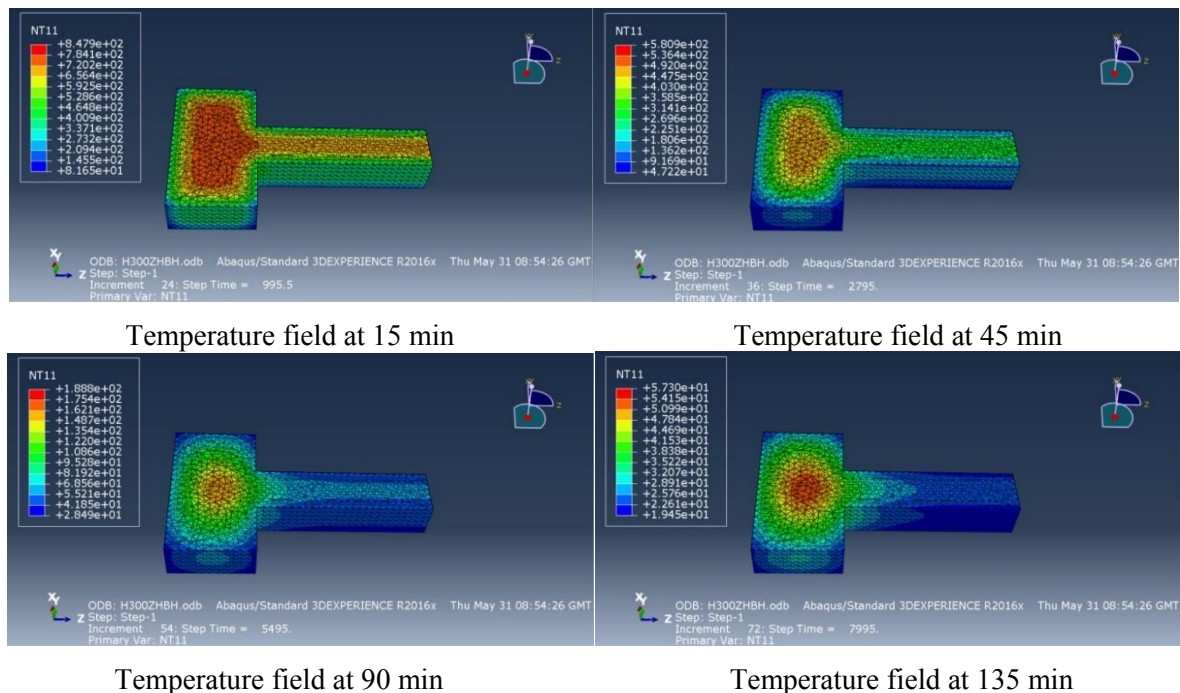


**Figure 6.** Simulated temperature field with dynamic heat transfer coefficient

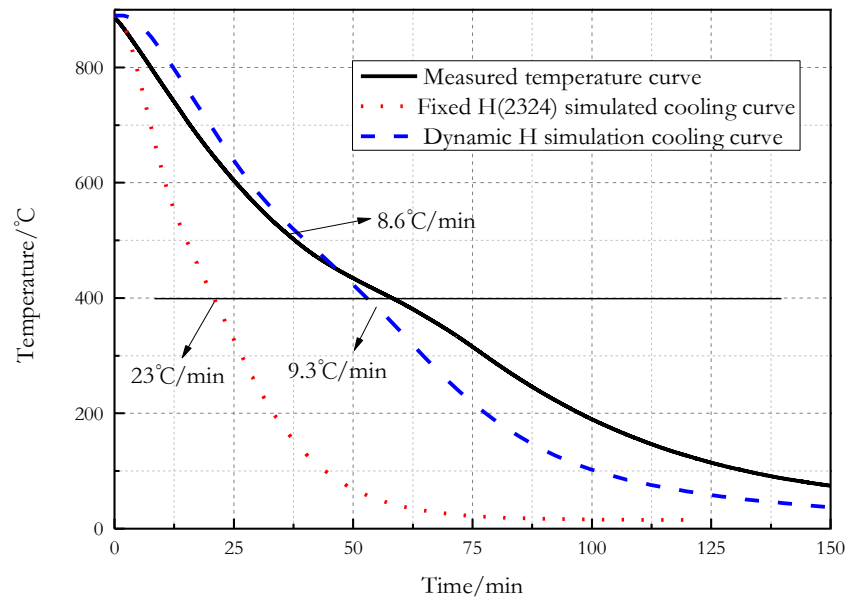


**Figure 7.** Simulated and measured temperature curve at 1/4 wall thickness in the sample area

#### 4. Simulation of tempering temperature field

##### 4.1. Radiation heat transfer coefficient and convective heat transfer coefficient

The tempering process is a relatively slow process. Since the nuclear forgings are heated in an electric furnace with good sealing performance, the temperature rising process can be regarded as an approximate radiation heat exchange process. The radiation heat transfer coefficient formula is as follows [2]:

$$H_s = 5.768\varepsilon \frac{\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{T_w + 273}{100}\right)^4}{T_c - T_w} \quad (8)$$

$\varepsilon$  is the radiance and is estimated by the following formula:

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_w} + \frac{A_w}{A_0} \left( \frac{1}{\varepsilon_0} - 1 \right)} \quad (9)$$

$\varepsilon_0$  is the emissivity of the furnace refractory, generally taking 0.82;  $\varepsilon_w$  is the surface emissivity of the workpiece, which varies with temperature. The radiance of steel can be calculated as follows:

$$\varepsilon_w = 0.24 \exp\left(\frac{T_w + 20}{1000}\right) \{ [1 + \sin(0.122T_w - 2.44)] \times 0.77 \} \quad (10)$$

$A_w, A_0$  corresponds to the work piece and the surface area of the furnace.

If the furnace temperature is not uniform, or if the furnace is too large compared to the forging, then even in the tempering stage, there will still be some convective heat transfer. At this time, the convective heat transfer is calculated by the following formula [2]:

$$H_k = \frac{\lambda_0}{h} Nu \quad (11)$$

$H_k$  is the convective heat transfer coefficient,  $\lambda_0$  is the thermal conductivity of the medium. The thermal conductivity of air at different temperatures at one atmosphere is shown in Table 2.  $H$  is the workpiece size (m). Take the shaft member for example,  $h$  take the axis length when it is vertical and the diameter when it is horizontal.  $Nu$  is the Nusselt number.

$$Nu = C(Gr \cdot Pr)^n \quad (12)$$

$Gr$  is the Grashof number.  $Pr$  is the Prandtl number.  $C$  and  $n$  are constants, which are related to the structure of the furnace. The determination method is as follows:

(1) Determine the Grashof number

$$Gr = \frac{0.036h^3 |T_w - T_c|}{\nu_0^2} \quad (13)$$

$T_w$  is the workpiece temperature.  $T_c$  is the ambient temperature.  $\nu_0$  is the viscosity of the environmental medium.

$$20-400^\circ\text{C}: \nu_0 = (0.013T + 12.58) \times 10^{-6}$$

$$400-1200^\circ\text{C}: \nu_0 = (0.199T - 14.95) \times 10^{-6}$$

$T$  is the boundary layer temperature, taking the average of the work piece temperature and the ambient temperature.

(2) Determine the Prandtl number

$$20-250^\circ\text{C}: Pr = -0.00028T + 0.726$$

$$250-1200^\circ\text{C}: Pr = -0.00010T + 0.68$$

(3) Determine the  $C$ ,  $n$  constant according to the product of  $Gr$  and  $Pr$ .

In this way, the total heat transfer coefficient is  $H = H_k + H_s$ .

**Table 2.** Thermal conductivity of an atmospheric air at different temperatures

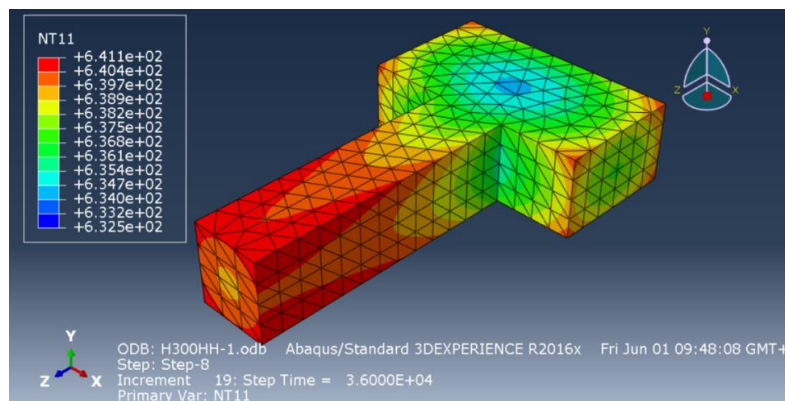
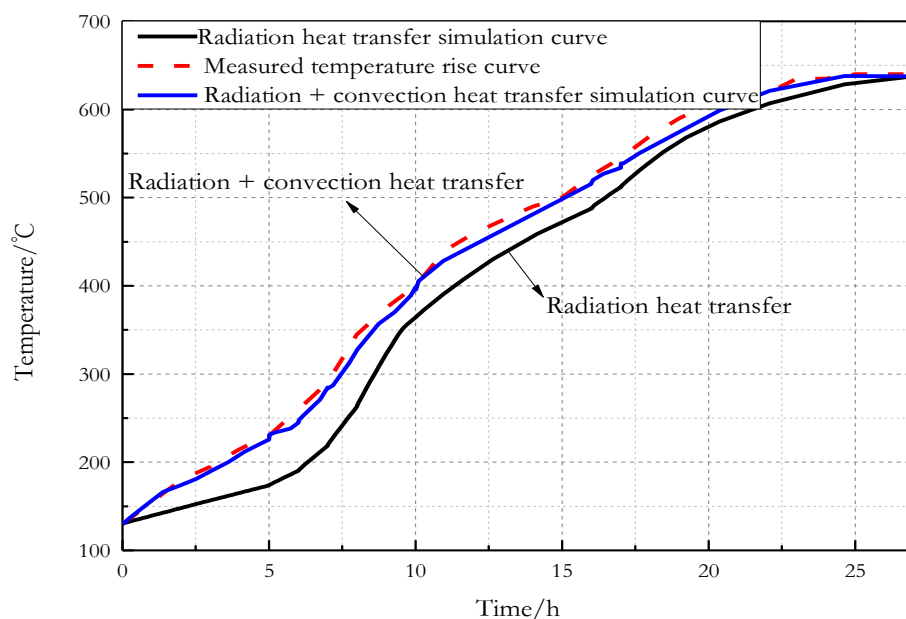
| Temperature T<br>/°C | Thermal Conductivity $\lambda \times 10^{-2}$ / W/(m·K) |
|----------------------|---------------------------------------------------------|
| 26.85                | 2.554                                                   |
| 126.85               | 3.224                                                   |
| 226.85               | 3.852                                                   |
| 326.85               | 4.480                                                   |
| 426.85               | 5.066                                                   |
| 526.85               | 5.652                                                   |
| 626.85               | 6.238                                                   |
| 726.85               | 6.783                                                   |
| 826.85               | 7.327                                                   |
| 926.85               | 7.829                                                   |
| 1026.85              | 8.374                                                   |
| 1126.85              | 8.918                                                   |

**Table 3.** Determination of constants C and n

| $Gr \times Pr$                        | C     | n     |
|---------------------------------------|-------|-------|
| $\leq 10^{-3}$                        | 0.5   | 0     |
| $1 \times 10^{-3} \sim 5 \times 10^2$ | 1.18  | 0.125 |
| $5 \times 10^2 \sim 2 \times 10^7$    | 0.54  | 0.25  |
| $2 \times 10^7 \sim 1 \times 10^{13}$ | 0.135 | 0.33  |

#### 4.2. Simulation results of tempering temperature field

Fig. 8 is a temperature field distribution diagram after the warming of the test plate forgings was completed. Figure 9 is a comparison chart of the simulated temperature rise curve and the measured temperature rise curve of the sample detection zone. It can be seen that if we only consider the radiation heat transfer, the temperature rise of the simulation curve is lagging behind the real curve. After considering the convective heat transfer, the simulated heating curve and the measured curve are highly matched. This shows that even in an electric furnace with excellent sealing and uniform hot zone, there also exists convective heat transfer.

**Figure 8.** Temperature field distribution of thick-walled test plate forgings after temperature rise**Figure 9.** Comparison of simulated heating curve and measured heating curve

## 5. Conclusion

(1) Using ABAQUS finite element software, the quenching cooling temperature field and tempering temperature field of 300mm thick-wall nuclear evaporator test forgings were successfully simulated, with high simulation precision and predictive significance.

(2) For large nuclear forgings, the quenching equipment did not significantly reduce the film boiling stage of the quenching process. It is not possible to simulate the quenching process of large wall thickness nuclear products with a fixed surface heat transfer coefficient as a parameter. The surface heat transfer coefficient derived from the inverse heat transfer method should be used as the simulation parameter.

(3) For large nuclear forgings, the tempering and heating process should consider both radiative heat transfer and convective heat transfer.

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