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Numerical Simulation of Turbine Disk Cooling

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Abstract

Turbine disk is a very important component, and the cooling rate reflected in the heat treatment process has a great impact on its macro performance. Therefore, by means of numerical simulation, this paper makes an exploratory study on the cooling process of turbine disk in air and oil, and obtains the corresponding numerical calculation model which can be used to predict the heat treatment of turbine disk under different working conditions, At the same time, it is found that the cooling rate of the outer surface is much greater than that of the inner surface, and the cooling rate of oil is much greater than that of air.

Keywords*: Turbine disk; Heat treatment; numerical simulation*

I. INTRODUCTION

Turbine disk is one of the most important components in aerospace engine [1,2]. In order to achieve high strength and hardness and obtain fine precipitate grain structure, it is necessary to ensure high cooling rate during its heat treatment; Then, too fast cooling rate will bring greater stress and deformation to the parts [3,4], cause cracking and deformation [5,6], and lead to parts scrapping in serious cases [7-10]. Therefore, it is necessary to study the temperature distribution and cooling rate during the heat treatment of turbine disk, so as to control its reasonable cooling rate and do no harm to turbine disk.

By means of computer simulation, the temperature change in the cooling process of turbine disk can be simulated and predicted, and the influence degree of relevant parameters can be analyzed, which has guiding significance for optimizing the process. At the same time, compared with the traditional experimental methods, numerical simulation can greatly speed up the research process and reduce the

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cost [11,12]. A large number of numerical simulation studies have been done on the heat treatment analysis of metal materials at home and abroad, including the thermodynamic analysis [13,14] and stress change [15,16] of the heat treatment process, but the fluid solid coupling analysis of the heat treatment process has not been fully studied. Therefore, the cooling process of turbine disk in air and oil is studied by numerical simulation in this paper.

II. ESTABLISHMENT OF CALCULATION MODEL

Mathematical model

The cooling process of turbine disk in air and oil is a typical incompressible fluid flow and coupling heat transfer problem. Therefore, the three-dimensional numerical simulation calculation method is used to solve it. This process meets three basic conservation laws in Physics: mass conservation law, momentum conservation law and energy conservation law [17,18]. At the same time, the flow in this problem is very complex and belongs to the category of turbulent flow. Therefore, the numerical equation of turbulence is involved. In this paper, the standard model is selected for numerical simulation.

Differential expression of mass conservation equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (1)$$

ρ is density , it is constant. t is time. The components of the velocity vector is $\vec{u}$, which is on the rectangular coordinate axis are u , v , and w .

The differential expression of momentum conservation equation is as follows:

$$\frac{\partial(\rho u)}{\partial t}+\mathrm{div}(\rho uu)=\mathrm{div}(\mu \mathrm{grad} u)-\frac{\partial p}{\partial x}+S_u \quad (2)$$

$$\frac{\partial(\rho u)}{\partial t}+\mathrm{div}(\rho vu)=\mathrm{div}(\mu \mathrm{grad} v)-\frac{\partial p}{\partial y}+S_v \quad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+\mathrm{div}(\rho wu)=\mathrm{div}(\mu \mathrm{grad} w)-\frac{\partial p}{\partial z}+S_w \quad (4)$$

μ is the dynamic viscosity coefficient, p is the pressure acting on the micro element fluid, S_u , S_v and S_w are the generalized source terms.

The differential expression of the energy conservation equation is as follows:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}+\frac{\partial(\rho wT)}{\partial z} =\frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right)+S_T \quad (5)$$

c_p is the specific heat capacity, T is the temperature, k is the thermal conductivity of the fluid, S_T is the viscous dissipation term.

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The governing equations of incompressible fluid flow are composed of equations (1) ~ (5). There are 5 independent unknowns ,which are u , v , w , p and T .There are independent equations, so the equations can be solved numerically.

Physical model

The turbine disk model used in this calculation is modeled according to the solid drawing. Firstly, it is assumed that the turbine disk is a rigid body without any deformation during cooling; Therefore, the numerical calculation physical model of turbine disk is obtained, as shown in Figure 1.

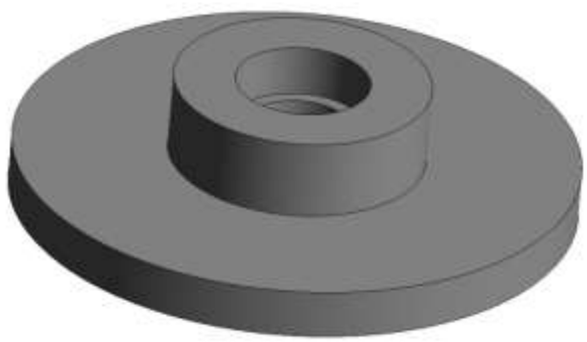

Figure 1: Turbine disk numerical calculation physical model

Secondly, the combination of air cooling and oil cooling is simplified into two independent cooling processes; Finally, due to some difficulties in the simulation of cooling oil stirring effect, the motion mode of turbine disk in oil is the same as that in air, which is simplified to the cooling mode of fluid flow, so as to reduce the difficulty of simulation. Therefore, the geometric and physical model of numerical simulation in this paper is established, as shown in Figure 2.

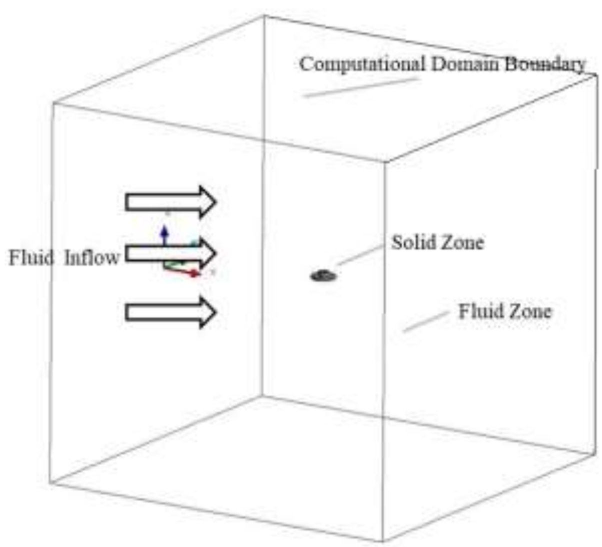

Figure 2: Computational domain model

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Meshing

In the process of calculating the cooling of the turbine disk, the situation of the turbine disk area is the focus of our concern. Therefore, we need to reasonably layout the density of the grid, so as to reduce the number of grids on the basis of ensuring the calculation results, so as to save computing resources[19,20]. When meshing, the calculation model can be divided into two areas close to and away from the turbine disk, and the grid near the turbine disk can be densified. The grid on the surface of the turbine disk is shown in Figure 3.

Figure 3: Turbine disk surface mesh

From the global grid distribution in the computing domain, it can be seen that the grid away from the turbine disk area gradually increases the grid scale in a gradual manner,the total number of grids in the calculation model is 8 million.as shown in Fig. 4.

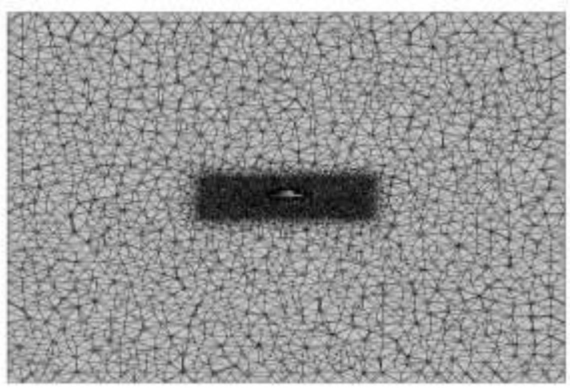

Figure 4: Global grid distribution

Solution parameter setting

In the cooling simulation of turbine disk, the principle of relative motion can be used to simulate the relative motion between turbine disk and surrounding fluid, set the incoming velocity of fluid, and the turbine disk is stationary. At the same time, the problem is transient, so it is also necessary to set the time step of calculation, that is, the time interval of each calculation, and give the initial value of calculation.

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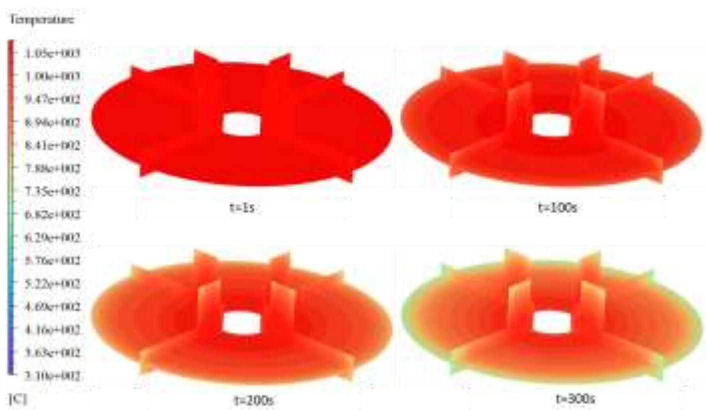
Example 1: the initial temperature of the turbine disk is 1080 ℃, the air is cooled for 1350s, the air temperature is 20 ℃, the incoming wind speed is 1m / s, the calculation step is 10s, and the calculation step is 120.

Example 2: the initial temperature of turbine disk is 1080 ℃, the cooling oil is cooled for 230s, the cooling oil temperature is 45 ℃, the incoming oil velocity is 1m / s, the calculation step is 1s, and the calculation step is 120.

Comparison of experimental data: after cooling in air for 180s, the surface temperature of turbine disk is 900 ℃, and the cooling efficiency of oil is 10 times that of air[21].

III.RESULT ANALYSIS

Simulation analysis of turbine disk cooling in air



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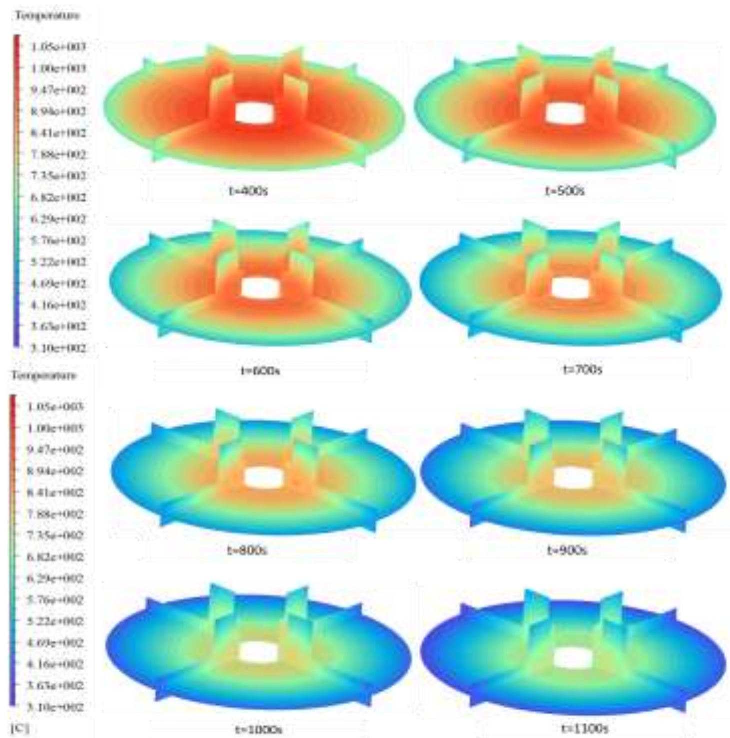

Figure 5: Turbine Disc Temperature Profile at Various Times of Cooling Process in Turbine Disk in the Air

Fig. 5 is a cloud diagram of the internal section of the turbine disk at several time points during the cooling process in the air. It can be concluded from the figure that the temperature of the turbine disk presents a certain gradient change from the outer surface to the inner core, which is caused by the heat transfer inside the turbine disk; At the same time, the temperature at the outer surface of the turbine disk decreases faster, while the inner surface is relatively slow, because the convective heat transfer between the outer surface and the fluid is more intense, while the heat transfer at the inner surface is less due to the restriction of fluid flow.

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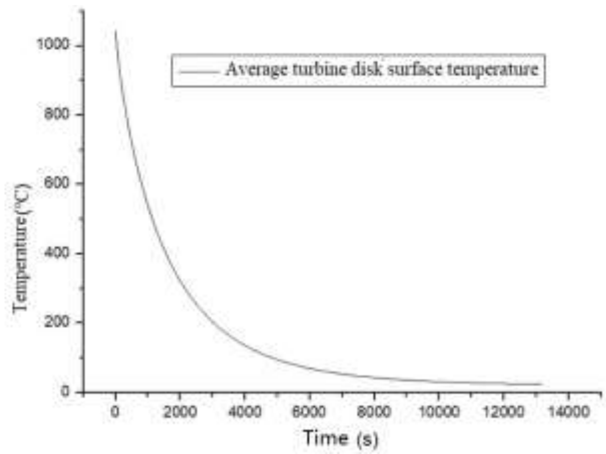
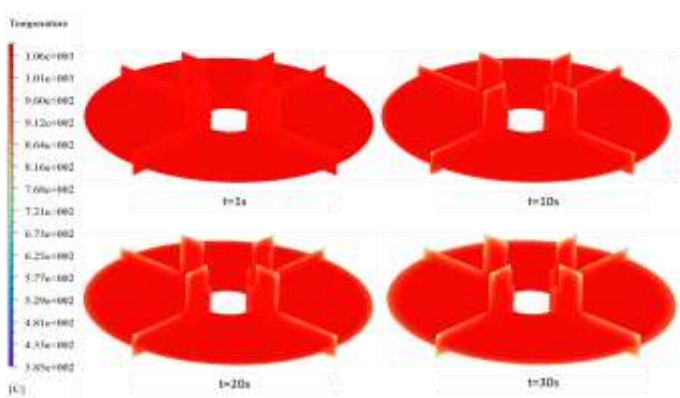


Figure 6:The curve of the mean surface temperature of the cooling process in the air in the turbine disk over time

Fig. 6 is the variation curve of the average surface temperature of the turbine disk with time during the cooling process in air.The average value of turbine disk surface refers to the average value of all surfaces. It can be seen from the figure that the surface temperature decreased to 900.97 ℃ at 180s, which is consistent with the experimental value of 900 ℃ at that time. Therefore, it is considered that the calculation result of the example is reliable and can be used to predict the surface and internal temperature of the turbine disk at each time. At the same time, it can be seen from the curve in the figure that the temperature decreases rapidly at the beginning of cooling, slows down with the passage of time, and will eventually stabilize at the temperature point consistent with the surrounding environment.

Simulation analysis of turbine disk cooling in oil



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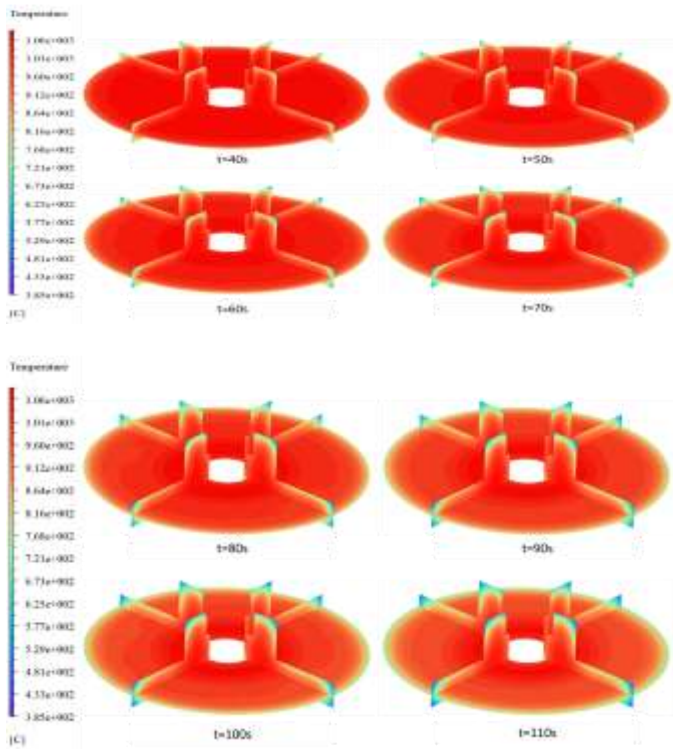

Figure 7: Turbine Disc Temperature Profile at Various Times of Cooling Process in Turbine Disk in the Oil

Fig. 7 is a temperature cloud diagram of the turbine disk section at several time points during the cooling process of the turbine disk in oil. It can be seen from the figure that the temperature of the turbine disk presents a certain gradient change from the outer surface to the inner core, which is similar to the cooling process in air; At the same time, the temperature on the outer surface of the turbine disk decreases rapidly, while the temperature on the inner surface is relatively slow.

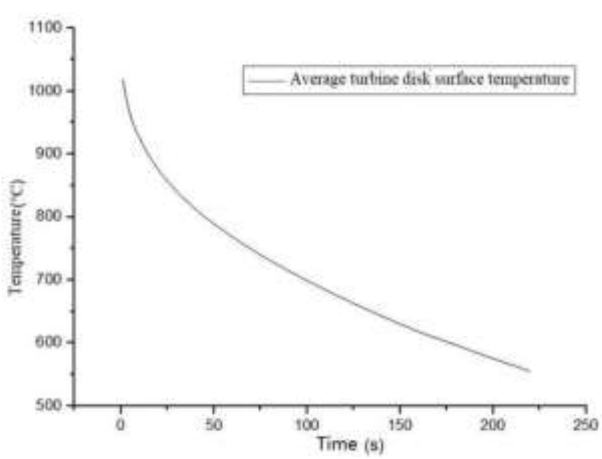

Figure 8: Turbine Disc Temperature Profile at Various Times of Cooling Process in Turbine Disk in the

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Oil

Fig. 8 is the variation curve of the average surface temperature of the turbine disk with time during the cooling process of the turbine disk in oil. The average value of turbine disk surface refers to the average value of all surfaces. In the cooling process of turbine disk in cooling oil, due to the existing experimental results, the efficiency of oil cooling is 10 times that of air cooling.so we can think that in the process of oil cooling, the surface temperature of turbine disk should be reduced to 900 ℃ at 18S, which is consistent with the actual situation. From the curve, it can be obtained that the surface temperature of turbine disk at 18S is 883.35 ℃, It basically matches the experimental values, so we can think that the calculation result of the example is reliable and can be used to predict the temperature on the surface and inside of the turbine disk at all times. At the same time, it can be seen from the variation curve of the average surface temperature of the turbine disk with time that the temperature decreases rapidly at the beginning of cooling, slows down with the passage of time, and will eventually stabilize at the temperature point consistent with the surrounding environment.

IV.CONCLUSION

(1) It is preliminarily concluded that the numerical simulation method can be used to calculate and analyze the cooling process of turbine disk in air and oil, and the results are reliable.

(2) In the cooling process of turbine disk, the cooling rate of outer surface is much higher than that of inner surface, and the cooling rate of oil is much higher than that of air.

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