

The heat transfer characteristic of the reactor coolant pump canned motor

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Abstract. This paper deals with the heat transfer characteristic of the reactor coolant pump canned motor. The cooling of the canned motor is an important issue for the design of the pump. In order to analyze the heat transfer characteristic of the canned motor, firstly the electromagnetic field of the canned motor is calculated with finite element method, and the magnetic resistance loss is gotten, then the heat distribution of the canned motor is obtained based on the electromagnetic field, finally the flow field and temperature field of the canned motor is calculated with CFD methods. The calculation indicates that the highest temperature and highest temperature rising are both occurred at the end winding.

1. Introduction

The reactor coolant pump is the only long-term continuously running key equipment of the primary coolant system of the nuclear power plant. Recent advanced large-scale pressurized water reactors regularly adopt the canned motor pumps as their reactor coolant pumps. The canned motor pump is driven by a canned motor, in which the coils of the rotor and the stator are both protected by the metal can. As its special structure、electromagnetic loss distribution、heat emission condition and work condition, the internal temperature distribution and the heat dissipation is very complicated, so it is necessary to analyze the temperature field of the canned motor..

In fact, many studies have been done on the temperature field analysis of the canned motor [1-6]. Paper [1] analyzed the temperature field of the reactor coolant pump canned motor. Paper [2] proposed a coupled thermal–magnetic analysis of an induction motor (IM) with the primary goal of achieving a rapid and accurate prediction of the IM performance. Paper [3] proposed a simplified thermal model for



variable-speed self-cooled induction motors and has been experimentally verified. Paper [4] dealt with the formulations used to predict convection cooling and flow in electric machines. Paper [5] offered a systematic approach to magnetothermal FEA. Paper [6] presented the study of the motor and the converter temperatures at rated and overload working conditions.

Determining the heat transfer characteristics of the walls to the fluid is the key issue for the heat transfer research of the motor. Paper [7-14] have done lots of work on how to determine the heat transfer characteristics of the rotating cylinder wall. But up to now there's still no definite conclusion. More work is needed.

In this paper, firstly the electromagnetic field of the canned motor is calculated with finite element method, and then the heat distribution of the canned motor is obtained based on the electromagnetic field, finally the temperature field of the reactor coolant pump canned motor is analyzed with thermo-hydro-solid coupled method.

2. Calculation Model

The temperature field simulation of the solid domain is based on the three dimensional steady state heat conduction equations which could be expressed by equation (1)

$$\begin{cases} \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) = -q \\ T|_{S_1} = T_0, k \frac{\partial T}{\partial n} |_{S_2} = q_0 \\ k \frac{\partial T}{\partial n} |_{S_3} = -\alpha(T - T_f) \end{cases} \quad (1)$$

where T is the temperature of the object, k is the thermal conductivity, q is the heat volumetric flow rate, S_1 is a boundary surface with constant temperature while T_0 is the temperature of it, q_0 is the heat flow rate of S_2 and T_f is the temperature of the surrounding fluid.

The temperature field simulation of the fluid domain is based on the equations which are expressed by equation (2)-(4)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

$$\begin{cases} \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} \right) - \frac{\partial p}{\partial x} \\ \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right) - \frac{\partial p}{\partial y} \\ \frac{\partial(\rho wu)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z} \right) - \frac{\partial p}{\partial z} \end{cases} \quad (3)$$

$$\frac{\partial(\rho uT)}{\partial x} + \frac{\partial(\rho vT)}{\partial y} + \frac{\partial(\rho wT)}{\partial z} = \frac{\partial}{\partial x} \left(\frac{\lambda_t}{c_p} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\lambda_t}{c_p} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\lambda_t}{c_p} \frac{\partial T}{\partial z} \right) \quad (4)$$

where u 、 v 、 w are the velocity components of x 、 y and z direction respectively, ρ is the fluid density, μ is the dynamic viscosity, p is the pressure of the fluid, c_p is the specific heat capacity of the fluid, T is the temperature of the fluid, λ_f is the thermal conductivity of the fluid[15].

3. Electromagnetic Field Calculation

Electromagnetic field calculation is the fundment of heat distribution and temperature field calculation. The modelling of the motor consists of two parts: 1) the general section, which includes the iron core and coils of the stator, the coils and squirrel cage of the rotor; 2) other metal components, which include the shielding of the rotor, finger clamp and the conical ring of the stator. The modelling of the general section is achieved by Maxwell while other metal components is modelled by CAD after which the model is imported to the finite element simulation software Maxwell. The model of the general section and the whole motor are showed in figure 1 and figure 2. The half model is used in the calculation to reduce computational time. Maxwell has applied the self-adaptive grid technique which can refine the grids step by step according to the computational accuracy of setting. But assigning the mesh scale of some special components is also required for faster convergence speed and better solving accuracy. The total simulation time is 1.5s in which there is 0.5s before the motor start to run. The variable time step method is applied in the calculation as the time step was 1ms in the first 0.5s while the time step changed to 0.4ms after that. The 3-D electromagnetic field of the motor is gotten in the calculation. Figure 3 and figure 4 are the magnetic strength distribution of the motor and the magnetic force line distribution of the end-winding respectively. These results are used in the latter calculation.

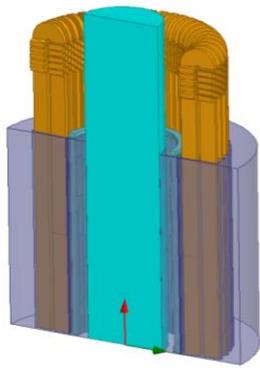


Figure 1. The 3-D model of the general section.

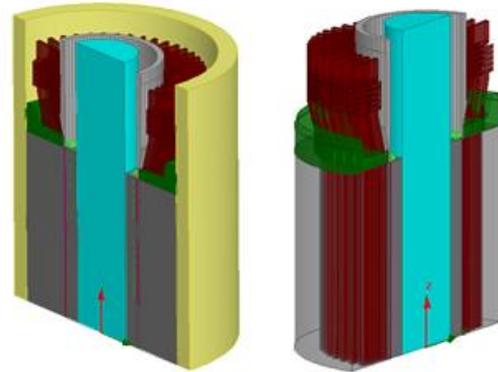


Figure 2. The complete model of the motor.

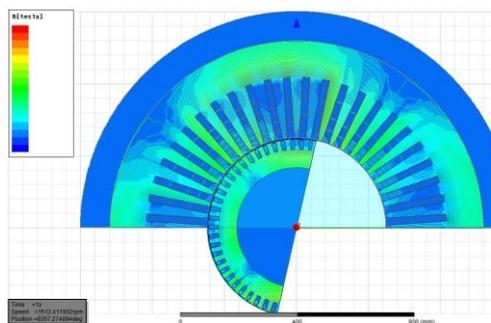


Figure 3. The magnetic strength distribution of the motor.

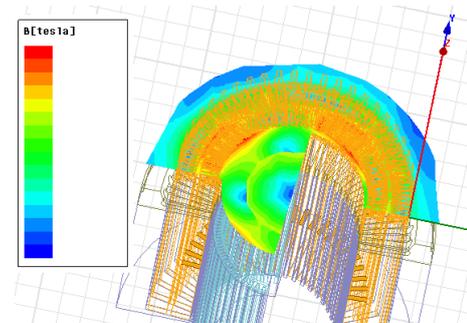


Figure 4. The magnetic force line distribution of the end-winding.

4. Heat Distribution

As the electromagnetic field of the motor has been gotten in the electromagnetic field calculation, the heat distribution can be calculated, and this is the basis of the temperature field calculation. The power consumption of the motor in different components are converted to heat of these parts, so the heat distribution can be calculated from the power consumption. The power consumption of the motor mainly takes place by three means: iron core loss, eddy current loss and coil loss. Figure 5-8 has given out the results of these losses respectively, which reflect the eddy current loss has the largest contribution to the motor power consumption. Meanwhile, the stator shield loss is the main part of the eddy current loss.

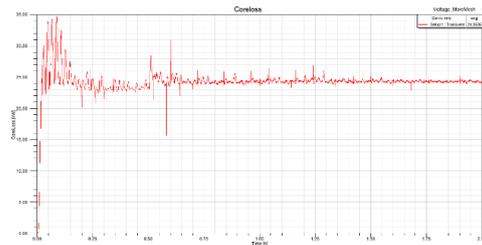


Figure 5. The iron core loss.

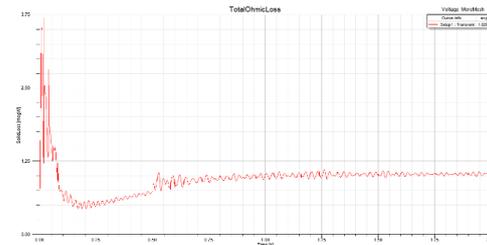


Figure 6. The eddy current loss.

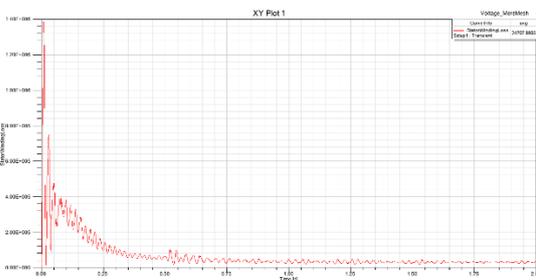


Figure 7. The stator coil loss.

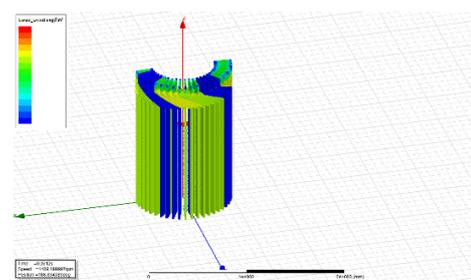


Figure 8. The contour of stator coil loss - axonometric drawing.

5. Temperature Field of The Motor

With the heat distribution of the motor, the temperature field can be analyzed. The calculation has taken the heat convection in the motor gap and the heat conduction in different motor components into consideration. There are some assumptions in the calculation: 1) the flow in the canned motor belongs to the turbulent flow as the Reynolds number of the flow is relatively high ($Re > 2300$), the turbulence model is $k-\epsilon$ model; 2) as the gas flow rate in the motor is far below the sound speed (the Mach number is very low) and the compressibility of water is negligibly small, all of the fluid in the motor are regarded as incompressible; 3) as the calculation is a steady state simulation, the time terms in the calculating equations are ignored.

The calculation is carried by ANSYS FLUENT 14.0. According to the symmetric structure of the motor and the above assumptions, the physical model takes 1/8 part in the circular direction and the whole length in the axial direction as figure 9 shows. Figure 10-12 shows the mesh details of the physical model, the total number of the grid is 6,600,152 while the grid number of the end winding cavity area is 1,605,378, the grid number of the external water jacketed clearance flow area is 172,800 and the grid number of the internal clearance flow area is 2,000,000. The mesh type of the clearance flow is hexahedral and other parts are tetrahedral.

The calculation takes the power consumption of each part as the heat boundary conditions and put them homogeneously on the solid calculation domain. The calculation has also taken

the motor's stray-load loss which is considered as 1.5% of the motor's rated power into consideration, this heat source is put on the stator core calculation domain. The boundary conditions of the cooling water outlets are pressure boundary. For the model's heat transfer

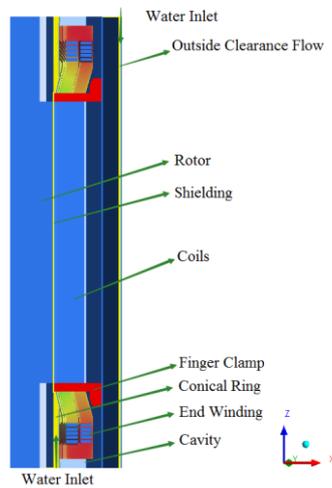


Figure 9. The calculation model.

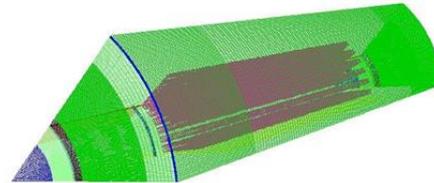


Figure 10. The mesh detail of the model.

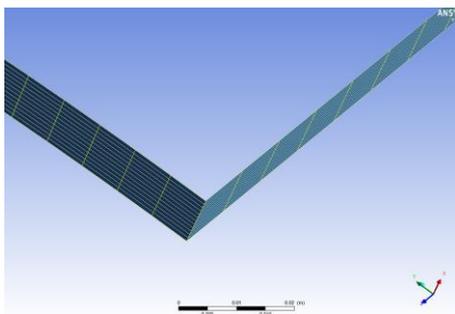


Figure 11. The mesh detail of the external water jacketed clearance flow area.

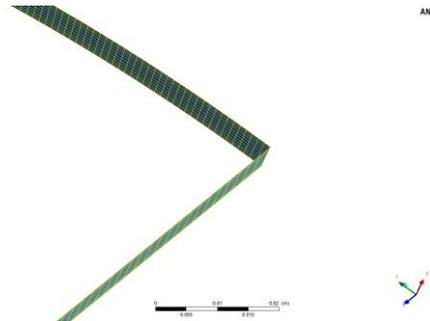


Figure 12. The mesh detail of the internal clearance flow area.

coefficients, the heat release coefficient of the motor's outside surface is $3.2 \text{ W}/(\text{m}^2 \text{ K})$ as this coefficient is decided by the characteristic scales and the fluid parameters which can be calculated by specific formulas, the heat transfer coefficients of the solid and fluid interfaces in the motor are acquired by flow-heat coupling method. The pressure coupling method is SIMPLEC which is widely used in incompressible fluid field calculation. The solver is chosen as a double precision solver and the iteration convergence precision is $1e-5$.

Figure 13-18 are the calculation results of the temperature field. From the results and the temperature rise distribution characteristic, one can find that the stator iron core, the rotor, the cooling water, the inner and outer jacket and the chassis have a relatively low temperature rising while the highest temperature and highest temperature rising are both occurred at the end winding. The highest temperature rising is as high as 127K.

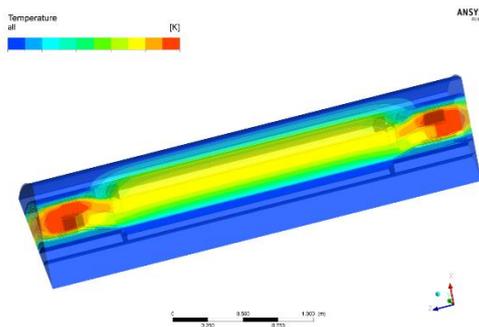


Figure 13. The Temperature field of the motor.

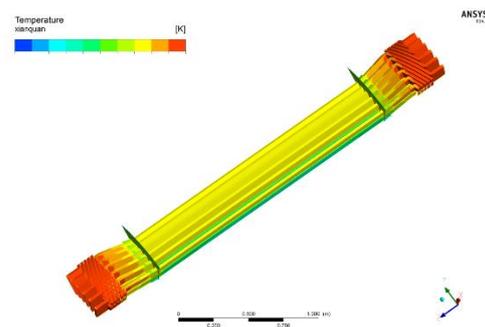


Figure 14. The Temperature field of the stator coil.

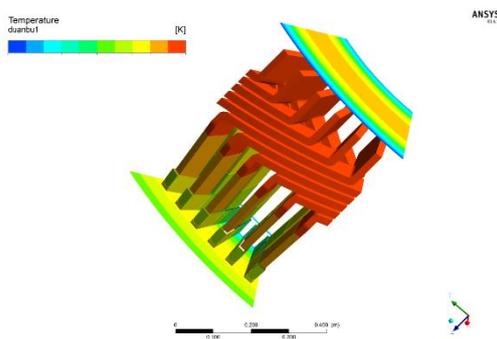


Figure 15. The temperature field of the end winding.

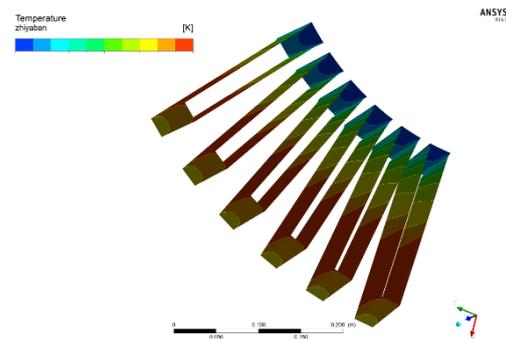


Figure 16. The temperature field of the finger clamp

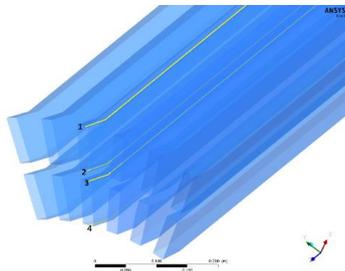


Figure 17. The value location of the stator coil.

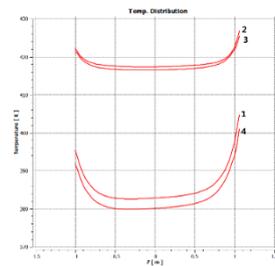


Figure 18. The temperature distribution of the stator coil.

6. Conclusions

In this work a series of computations have been carried to analyze the temperature field of the reactor coolant pump canned motor. The following conclusions could be summarized.

- This paper has achieved the canned motor's numeric analysis of the electromagnetic field, the temperature field and the fluid field, the results are reasonable compared to the practical operation experiences.
- The highest temperature and highest temperature rising are both occurred at the end winding, meanwhile the temperature in the middle are much higher than both ends and it has brought a prodigious temperature gradient, so the heat releasing of the end winding needs significant attention.
- The calculation has not gotten an experiment to validate its computational accuracy, further study is still required.

Acknowledgments

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