Test Analysis and Simulation Calculation of Temperature Field for Dry-Type Air-Core Reactor

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Abstract. Based on test analysis and simulation calculation of temperature field for dry-type air-core reactor, the temperature rise rule of internal axial dimension and enveloping internal conductor were analyzed. The highest temperature rise point in the envelope is located about 1/4 of the packet seal. The temperature rise difference between the inner wires is small, and the temperature rise difference within the envelope is less than 1 ℃. The radial distribution of temperature along the insulating impregnated glass fiber has a great gradient. The temperature in the middle of the airway is near room temperature, and the temperature rise is about 5K, and the internal temperature of the airway has a larger gradient. For airway width design, the influence of the change of the airway width of the temperature rise distribution should be considered.

1. Introduction

Dry-type air-core reactor has the advantages of low loss, low noise, simple maintenance, good linearity of reactance value and so on. Over the years, it has been more and more widely used in the power grid. This kind of equipment is generally used in the shunt reactor on the low voltage side of the substation. In recent years, many accidents of turn-to-turn breakdown and burnout of dry-type reactors have occurred in domestic power grid and provincial companies. From the perspective of the use and maintenance in the power grid, the imported and domestic hollow reactors will appear local overheating in varying degrees after a period of operation, and then gradually develop into turn-to-turn short circuit, burning loss, and even fire. These problems have attracted the attention of the power grid, production enterprises and researchers. More and more attention has been paid to the research of loss and temperature rise distribution of dry-type air-core reactor. Liu Zhigang and others from Xi'an Jiaotong University studied the temperature field distribution of dry-type air-core reactor based on the coupling method. The simulation and experiment showed that the hottest temperature rise of a certain type of reactor was at the upper end of the reactor, and the distribution of convection coefficient of the inner surface of three envelopes is given [1]. According to the structural characteristics of the reactor, Xia Tianwei and others from Shenyang University of Technology used different local heat transfer coefficients in different parts, established the differential equation of temperature field by using the principle of thermodynamics, and analyzed the temperature field of the dry-type air-core reactor. The calculation shows that when the width of the envelope is constant, the highest point of winding temperature is in the upper middle position. The difference between the highest temperature point and the lowest temperature point is 10 ℃. The maximum temperature rise of the reactor is 20-40 ℃ higher than the average temperature rise [2]. The research at home and abroad mainly focuses on the
temperature distribution of dry-type air-core reactor. However, there is a lack of relevant analysis and research on the temperature rise between the electromagnetic wires of each layer in the envelope, the temperature rise between the envelope surfaces, the axial temperature rise distribution of each envelope, and the relationship between the average temperature rise of the reactor and the hottest temperature rise [1-9]. These problems are the most concerned aspects in the design and operation of the reactor. In particular, there is a shortage of research on temperature distribution and inter-turn insulation state diagnosis of the reactor. Aiming at the above problems, the method of simulation analysis is respectively adopted and verified by experiments to solve the following two problems. (1) Find out the variation law of the axial temperature in the encapsulation to provide a basis for the measurement of the hottest temperature. (2) Find out the relationship between the inner conductor of the package and the relationship between the insulation thickness of the package and the temperature rise, so as to provide a reference for the insulation optimization design.

2. Simulation analysis
The model of fluid-solid coupled heat transfer + radiation heat transfer is adopted. Meanwhile, solid heat conduction, air heat conduction, air convection and radiation on the reactor surface are considered. Considering the axisymmetric structure of dry reactor, the two-dimensional geometric model of the reactor is established, as shown in figure 1.

![Figure 1. Modeling diagram of the reactor conductor and package.](image)

The thermal conductivity of polyester film is set to 0.2 W/m·K, the thermal conductivity of glass fiber and resin composite is 0.3 W/m·K, and the thermal conductivity of aluminum itself is 200 W/m·K. However, considering that the electromagnetic lines of all turns are modeled as an equivalent (equal cross-sectional area) rectangle, the radial composite thermal conductivity is 200 W/m·K of aluminum. According to the difference of wire diameter, the axial composite thermal conductivity is 1.8835, 1.948, 1.1443 W/m·K respectively.

The surface radiation absorption coefficient of the reactor is 0.95. The temperature field distribution of the reactor and its surroundings is shown in figure 2 and figure 3.

![Figure 2. Distribution diagram of overall temperature rise of the reactor.](image)
![Figure 3. Distribution diagram of temperature rise at the upper end of the reactor.](image)

3. Experimental analysis
The temperature rise prototype test model of CKGKL-10-60-6 is made. The temperature measuring probe is placed in the radial and axial direction of the package, which is used to measure the temperature rise distribution inside the package and to compare the temperature change inside and outside the package. The placement of the probe is shown in the following figure.
Figure 4. Schematic diagram of probe arrangement.

The radial probes are respectively placed in the middle of the inner insulation of the package, the outer side of the insulation of the first layer of wire, the outer side of the insulation of the second layer of wire, ..., and the middle of the outer insulation of the encapsulation. The offset between the probes is allowed to exist along the circumferential direction, so as to facilitate the arrangement of the probe.

The axial probes are respectively placed outside the electromagnetic wire in the middle of the package. The distance between the probes and the upper end is about 60mm. Considering the large temperature rise gradient in the upper half part of the reactor, it is the main concern and analysis target. Therefore, the distance between the probes is 30mm, and the distance between the probes in the lower half part is 60mm. The temperature of the reactor is obtained by applying 1.35 times the rated voltage and 1.35 times the rated current to the reactor.

In order to better analyze the temperature change along the radial and axial direction of the package, the following axial and radial positions are selected to analyze the temperature rise distribution: $x = 800, 900, 1000, 1200$ (equivalent to 250mm under the end insulation), $y = 0.35$ (1 encapsulation inner surface), $y = 0.0358565$ (1 encapsulation 2 layer outside the line), $y = 0.3644$ (1 encapsulation outer surface), $y = 0.3894$ (2 encapsulation inner surface), $y = 0.395135$ (2 encapsulation 2 layer outside the line), $y = 0.3994$ (2 encapsulation outer surface), $y = 0.4244$ (3 encapsulation inner surface), $Y = 0.43237$ (3 encapsulation 3 layer outside the line), $y = 0.43865$ (3 encapsulation outer surface).

3.1. Validity analysis of simulation results
The simulation calculation itself is a means of experiment and a concrete supplement to the entity test. However, only when the simulation result is verified by the test data, can it have the significance of practical application.

Figure 5 is a comparison diagram of $x = 1200$mm, that is, the radial temperature rise distribution of the upper end of the coil. From the match between the simulation calculation results and the test data, the simulation calculation results are consistent with the measured temperature rise data, but show different characteristics in different envelopes. First of all, in the innermost and outermost envelope, the deviation of the temperature rise result of the simulation calculation is about 5K. This has a great relationship with the quality of the innermost and outermost encapsulation heat dissipation conditions, and the lack of consideration of radiation heat dissipation by the software itself. This deviation is within the range of engineering design and measurement. The optimization of the model is left for follow-up research. Secondly, the simulation temperature rise of tundish seal is completely consistent with the test temperature rise, which proves the validity of material parameters and simulation calculation model, and the simulation results can be used to guide the engineering design.
Figure 5. Comparison of radial temperature distribution of a reactor at x = 1200mm.

The comparison between the simulation results and the test results of the axial temperature rise outside the second layer line of the first package is shown in figure 6.

Figure 6. Comparison of simulated temperature rise with the measured temperature rise in the first envelope.

The comparison between the simulation results and the test results of the axial temperature rise outside the second layer line of the second package is shown in figure 7.

Figure 7. Comparison of simulated temperature rise with the measured temperature rise in the second envelope.

The comparison between the simulation results and the test results of the axial temperature rise outside the second layer line of the third package is shown in figure 8.
Figure 8. Comparison of simulated temperature rise with the measured temperature rise in the third envelope.

Figure 6 to figure 8 are the comparative analysis of the axial temperature rise distribution of different envelopes. It can be seen that there are different rules between the measured data and the simulation data of different envelopes. In addition, the matching of the axial temperature rise distribution is different from that of the radial temperature rise distribution. It is mainly manifested in the following three aspects.

1) The simulation results of the first package are generally large, but near the hottest spot, that is, at the upper end of the reactor, the two match well, and the deviation is less than 3K.

2) The second packet, that is, the intermediate packet, has the best match between the simulation calculation and the test data in the middle segment of the packet. Because of the influence of probe location on the upper end, it is impossible to draw a conclusion whether the trend of simulation results and test data changes near the hottest spot is consistent. The temperature difference between the two at the key point is also less than 3K.

3) For the third envelope, the simulation calculation and test data match well, especially near the hottest spot on the top of the envelope. The changing trends of the two are completely consistent, and the data deviation is less than 1K.

From the comparison and analysis of the above axial and radial simulation data and test data, the overall temperature rise difference between the two is less than 5K, and the temperature rise difference between the key points is less than 3K. The simulation calculation data trend is correct, and the key data points are accurate and effective, which has the value of guiding the engineering optimization design.

3.2. Research and analysis of the hottest spot

The heat dissipation conditions of different envelopes are quite different, so the distribution of the hottest spots in different positions is completely different, but it can be roughly divided into two categories: internal and external encapsulation and intermediate encapsulation. In order to facilitate the follow-up analysis, the research on the hottest spot of axial temperature rise takes the temperature rise distribution of the axis of the position of the second layer of electromagnetic wire as the research objective. The specific analysis is as follows. It can be seen from figure 6 to figure 8 that for the model product of the prototype, the hottest point temperature rise of the inner envelope is at the axial position of x = 1300mm; the hottest point of the middle envelope is at the position of x = 1350mm; the hottest point temperature rise of the outer envelope is at the axial position of x = 1330mm. According to the size ratio of package, the hottest spot of inside and outside package is 85-90% of the package height. The difference of each encapsulation position is not obvious. The actual engineering temperature rise measurement refers to this data.

3.3. Analysis of temperature rise distribution law of dry-type air-core reactor

As can be seen from the axial temperature distribution diagram, the highest temperature rise in the envelope is generally located at x = 1300 ~ 1350mm, that is, at the upper end of the envelope about 150mm, which is close to the top 1/5 of the envelope. As shown in figure 9 to figure 11, the axial
The temperature of the inner envelope gradually increased from close to room temperature to the maximum value, with a temperature rise of about 50K, then the temperature decreased, and the curve of temperature rise is arched.

Figure 9. Axial temperature distribution on the inner and outer surface of the first envelope and the outside of the second layer of the line.

Figure 10. Axial temperature distribution on the inner and outer surface of the second envelope and the outside of the second layer of the line.

Figure 11. Axial temperature distribution on the inner and outer surface of the third envelope and the outside of the third layer of the line.

The radial temperature distribution of $x = 1200\text{mm}$ is calculated by the simulation. The difference of temperature rise between the wires inside the enclosure is small. In this case, the difference of temperature rise inside the enclosure is within 1 ℃. The temperature distribution along the radial direction of insulated impregnated glass fiber has a large gradient. Due to the effect of natural convection, the internal temperature of the airway also has a large gradient, among which, the temperature in the middle of the airway is close to the room temperature, and the temperature rise is about 5K. For the design of small capacity products with this specification, the current airway width is slightly wider, and the optimization of width design is one of the directions of subsequent product design.

4. Conclusions

(1) Through experimental verification, the two-dimensional geometric model of the reactor can meet the actual operating conditions of the reactor. This model is established by adopting the model of fluid-solid coupled heat transfer + radiation heat transfer and considering the solid heat conduction, air heat conduction, air convection and radiation on the reactor surface. The variation trend of the simulation results is consistent with the measured results, and the axial and radial temperature rise distributions are in good agreement with each other. Generally speaking, the temperature rise difference between the simulation results and the test results is less than 5K, and the deviation between the simulation results and the test results can reach 1K. The simulation results are consistent with the test data and have good matching. It can be used as a reference for engineering design optimization.
(2) The highest point of temperature rise in the envelope is generally about 1/5 of the upper part of the envelope, which can provide a basis for the subsequent actual hottest temperature rise measurement.

(3) From the simulation of radial temperature distribution, the difference of temperature rise between the wires inside the envelope is small. In this case, the difference of temperature rise inside the envelope is within 1 ℃. The temperature distribution along the radial direction of insulating impregnated glass fiber has a large gradient.

(4) Due to the effect of natural convection, the temperature inside the airway has a large gradient. Among them, the temperature in the middle of the airway is close to room temperature, and the temperature rise is about 5K. For the airway width design, the influence of the airway width change on the temperature rise distribution should be reconsidered.

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