

Study on electromagnetic-thermal coupling heating process of electromagnetic induction heating device of circulating oil

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ABSTRACT

Transformer oil is usually heated by electrical heating devices, which has defects of high temperature of heating devices thus low reliability. Therefore, an electromagnetic induction heating device of circulating oil was proposed in this paper. An electromagnetic-thermal coupling model of the heating device was built, and the modeling results were verified by experiments. Using the model, the structure of heating tube of circulating oil is optimized, and temperature-velocity field synergy analysis for each tube was carried out. The results show that the alternating elliptical axis tube has better heat transfer performance and temperature uniformity than the circular or elliptic straight tube. At last, the thermal resistance networks of the electromagnetic induction heating device and the traditional electrical device were built. The thermal resistance analysis results show that the electromagnetic induction heating device has much lower temperature thus higher reliability than the traditional electrical heating device.

Keywords: electromagnetic induction heating, electromagnetic-thermal coupling model, structure optimization, field synergy, thermal resistance network

1. INTRODUCTION

Oil-immersed transformer is a very important equipment in power transmission line. In the process of transformer storage, installation, operation and maintenance, the moisture content of insulation oil will increase due to moisture exposure and aging of insulation oil, which will reduce the breakdown voltage of the transformer and seriously damage its reliability and service life [1]. Therefore, the transformer needs to

be heated and dried. At present, large oil-immersed transformers are mainly heated and dried by electrical heating devices [2]. The electric heating wires are wrapped by insulating enclosures and does not contact the oil directly, thus the thermal resistance is relative large and the electric heating wire temperature is high.

Compared with the traditional electrical heating method, the electromagnetic induction heating method is reliable and efficient, and can realize accurate control of heating power [3,4]. It is widely used in industrial heating, but it is rarely used in the field of transformer oil heating and drying [5,6].

Therefore, a transformer oil electromagnetic induction heating device was proposed in this paper. It is mainly composed of a power supply, a control circuit and electromagnetic heating tubes. The transformer oil is driven by an oil pump and flows circularly in the tubes. The electromagnetic-thermal coupling model of the heating device is established, and the structure of the heating tubes is optimized.

2. MODEL AND EXPERIMENTAL

2.1 Electromagnetic-thermal coupling model of the heating device

The electromagnetic induction heating tubes are composed of tubes, insulation layer and coil, as shown in Fig.1. The tubes are made of 20# low carbon steel, and the low resistivity of the iron can cause large eddy current induction, thus reducing the power loss of the power supply. The outer diameter of the tube is 34mm, the wall thickness is 3mm, and the tube length is 1m.

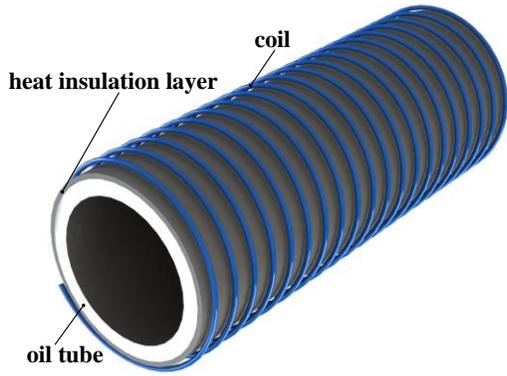


Fig 1 Heating tube structure.

The kinematic viscosity of the analyzed KI45X transformer oil varies greatly with temperature. In order to ensure the accuracy of modeling results, the relationship between kinematic viscosity and temperature should be determined. The kinematic viscosity of KI45X transformer oil at different temperatures is shown in Fig.2 [7].

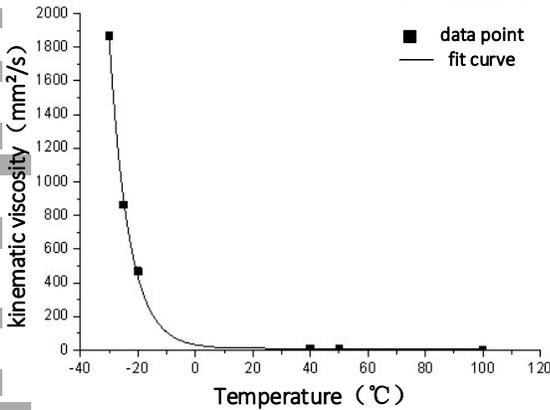


Fig 2 The relationship between the kinematic viscosity of transformer oil and oil temperature.

Other physical parameters of the transformer oil vary little with temperature and are assumed to be constants. Since the temperature of the steel tube does not exceed 100°C during the whole heating process, it is assumed that the physical parameters of the steel tube do not change with the temperature.

High-frequency AC current flows through the electromagnetic coil wound on the surface of the steel tube, generating alternating magnetic field and eddy currents inside the steel tube walls. Due to the low resistivity of the steel tube, a large amount of heat can be generated inner tube walls in a short time and the tube can be heated quickly. The electromagnetic model of the heating tube was built and the current frequency of the excitation source was set as 2.6 kHz in the model. The eddy current density distribution in the axial section of the tube walls was shown in Fig. 3(a). Due to the skin

effect of the tube walls [7], the eddy current density on the outer surface of the tube wall is larger than that on the inner surface, but it is uniformly distributed along the axial direction. The heat flux distribution of the tube wall shown in Fig.3(b) is consistent with the eddy current density distribution trend. The heat flux results will be set as boundary conditions of the thermal model of the heating device.

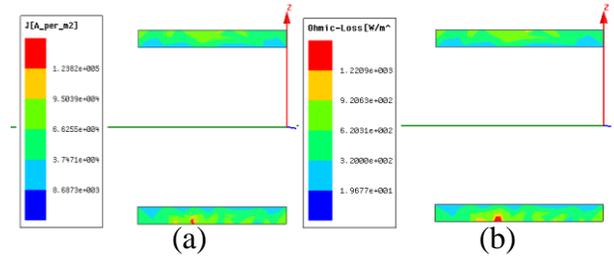


Fig 3 Distribution of eddy current density (a) and heat flux density (b) of tube wall.

2.2 Experimental verification

In order to verify the modeling results of electromagnetic-thermal coupling model, a test platform for transformer oil heating were built using straight round tube as shown in Fig.4. The KI45X transformer oil is circulated driven by a gear oil pump, and the volume flow of the transformer oil is detected by a gear flow meter. The transformer oil flows into the electromagnetic induction heating tube from the outlet of the oil tank, and returns to the oil tank after passing through the heating tube. A thermocouple installed on the outer wall of the heating tube is used to measure the wall temperature. The inlet and outlet oil temperature were also measured by thermocouples. The initial oil temperature of the transformer oil was 15°C, the electromagnetic induction heating power was 920 W, the flow rate of transformer oil was 1.8 m/s, and the transformer oil was expected to be heated to 60°C.

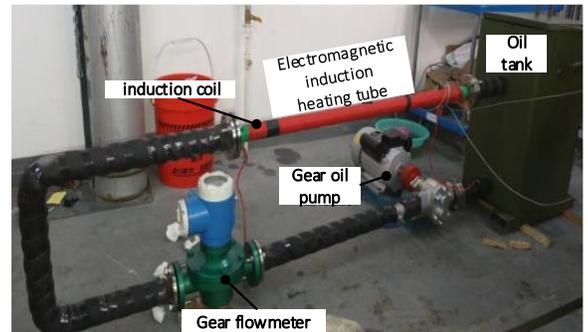


Fig 4 Electromagnetic induction heating experiment device.

Fig.5 shows the comparison of modeling results and experimental data. With the increase of inlet oil

temperature, the temperature of the outer wall of the tube also increases. The modeling results are in good agreement with the experimental data, and it shows the accuracy of the electromagnetic-thermal coupling model.

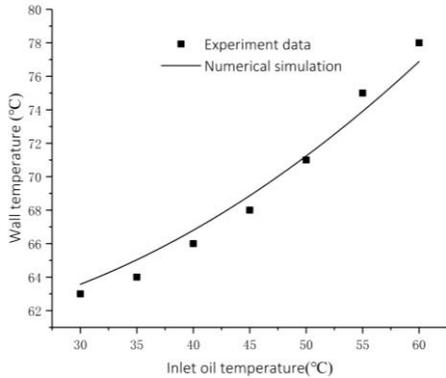


Fig 5 Comparison between numerical simulation and experimental data.

3. OIL TUBE STRUCTURE OPTIMIZATION

3.1 structure comparison

The straight round tube, the elliptic straight tube and the alternating elliptical axis tube are compared, as shown in Fig.6. All the three tubes have the same cross-sectional area and length of 1m. Under the same heating power, the flow field and temperature field distribution and field synergy number F_c of the three tubes were compared, and the influence of the increase of inlet oil temperature on the flow and heat transfer performance of the tubes was explored.

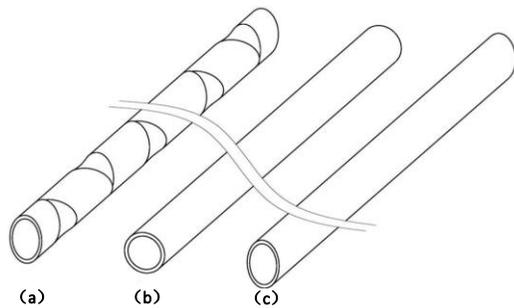


Fig 6 Three tube structures ((a) the alternating elliptical axis tube, (b) the straight round tube, (c) the elliptic straight tube).

3.2 The flow and temperature field distribution

Fig.7 shows the flow field and temperature field distribution of the three kinds of tubes at the inlet oil temperature of 30°C. In the flow field of the alternating elliptical axis tube, the transformer oil produces a violent secondary flow with the cross change of the elliptic

section, and the secondary flow develops into a longitudinal vortex under the action of inertia and viscosity. The generation of longitudinal vortices improves the heat transfer performance of the tube. While there is no longitudinal vortex in the circular tube or in the elliptical straight tube. From the temperature field distribution, it can be also seen that the temperature distribution of transformer oil is improved by the continuously changing flow cross section in the alternating elliptical axis tube. The isothermal lines in the alternating elliptical axis tube reveal that longitudinal vortices promote the transformer oil heating near the inner surface. While isothermal lines in the straight round tube and in the elliptical straight tube show the law of gradual decrease of transformer oil temperature from the inner surface to the center.

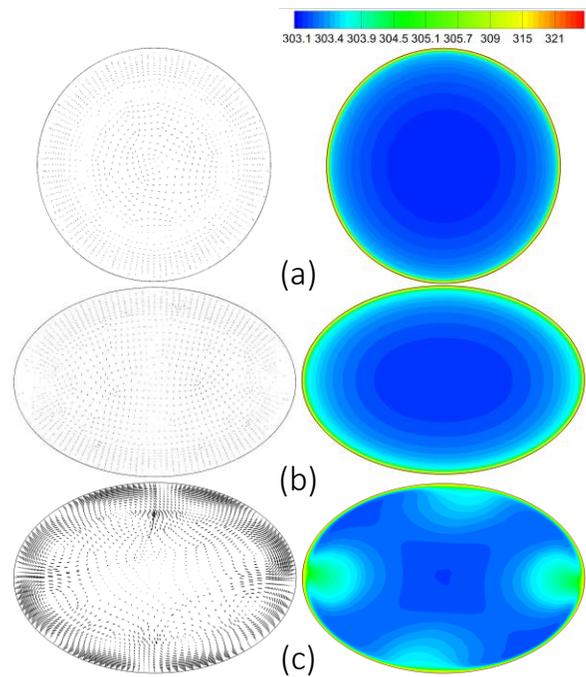


Fig 7 Flow field and temperature field((a) the straight round tube, (b) the elliptic straight tube, (c) the alternating elliptical axis tube).

3.3 Flow-temperature field synergy analysis

Flow-temperature field synergy number F_c [8] is used to quantitatively describe and compare heat transfer performance. The greater the field synergy number is, the better synergies between the velocity field and the temperature field will be, and the heating device has better heat transfer performance.

The field synergy number F_c can be expressed as:

$$F_c = \frac{Nu}{RePr} \quad (1)$$

Where Nu is the Nusselt number, Re is Reynolds number and Pr is Prandtl number.

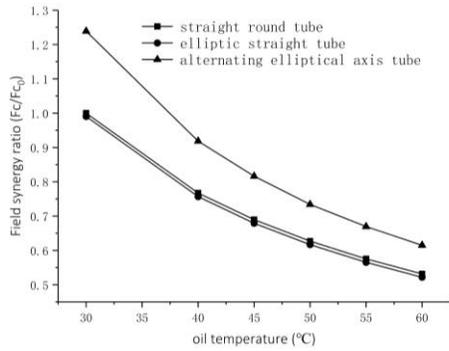


Fig. 8 Comparison of F_c/F_{c0} of three tubes.

In order to facilitate the comparison of F_c of different tubes under different oil temperatures, F_c of the round tube at the inlet oil temperature of 30°C was set as F_{c0} . At other temperatures, the ratio of F_c and F_{c0} was used as an indicator, and the results are shown in Fig. 8.

Compared with the straight round tube and the elliptic straight tube, F_c of the alternating elliptical axis tube is increased by more than 15%, which effectively improves heat transfer performance of the alternating elliptical axis tube. F_c of the three types of tubes all decreased with the increase of inlet oil temperature.

4. COMPARISON WITH TRADITIONAL ELECTRICAL HEATING DEVICE

Electric heating belt is a common heating method of resistance external heating transformer oil. The electric heating wire of the resistance external heating device is not in contact with transformer oil, so the heat transfer resistance is large and the heating efficiency is low. If the transformer oil is heated by a traditional electric heating wire, the electric heating wire is wrapped on the outer wall of the oil tube, as shown in Fig. 9(a). There is an insulating layer on the surface of the electric heating wire, and the material is generally silicone rubber or glass fiber. The electric heating wire is energized to generate heat, which is transmitted to transformer oil through insulation layer, air gap and tube wall in turn. The electromagnetic induction heating method is shown in Fig. 9(b). The tube walls heat up by itself and the heat is directly transferred to the transformer oil.

The thermal resistance values for the two heating modes are listed in Table 1. The total thermal resistance of electric heating wire is 6.76 times that of electromagnetic induction heating. Assuming that the added heat is 600W/m and the transformer oil temperature is 0°C , the core temperature of the electric heating wire is 187°C . The electromagnetic coil hardly

generates heat, and the temperature is close to the tube wall temperature, which is 28°C . Therefore, the temperature of the electromagnetic coil in electromagnetic induction heating is much lower than that of the electric heating wire in the traditional device under the same heating amount, which has higher reliability. Similarly, if the temperature of the heating element is the same, the added heat of electromagnetic induction is much higher than that of the traditional device, which greatly improves the heating efficiency.

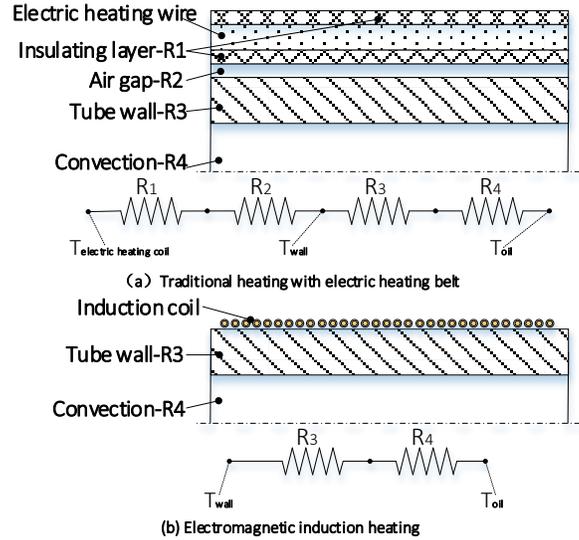


Fig. 9 Comparison of thermal resistance between two heating methods

Table 1 Comparison of the thermal resistance of the two heating methods (tube length is 1m, oil flow is $2.5\text{ m}^3/\text{h}$)

Materials	Conductivity ($\text{W/m}\cdot\text{K}$)	Thickness (mm)	Thermal resistance (K/W)	
			Traditional heating	Induction heating
Insulating layer	0.045	0.5	$R_1=0.104$	$R_1=0$
Air gap	0.029	0.5	$R_2=0.161$	$R_2=0$
Tube wall	57	3	$R_3=0.0005$	$R_3=0.0005$
Convection	/	/	$R_4=0.0455$	$R_4=0.0455$
The total thermal resistance			0.311	0.046

5. CONCLUSION

In this paper, the electromagnetic thermal coupling heating process of electromagnetic induction heating device is theoretically modeled and experimentally studied to verify the correctness of the model. The structure of the heating tube is optimized by the coupling model. Moreover, the performance of electromagnetic induction heating transformer oil is compared with the traditional electric wire heating method to reflect the

performance advantages of electromagnetic induction heating. After the above studies, the following conclusions can be drawn:

(1) The electromagnetic-thermal coupling analysis model of the electromagnetic induction heating transformer established is consistent with the experimental data;

(2) The application of cross elliptic tube to electromagnetic induction heating makes the temperature uniformity of transformer oil in the tube better, and the field synergy is improved by more than 15% compared with that of straight round tube and elliptic straight tube;

(3) Compared with traditional electric heating wire heating, electromagnetic induction heating has smaller thermal resistance, higher heating efficiency and better reliability;

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