Thermal Analysis and Structure Optimization of a Dry-type Transformer with Ceramic Insulated Windings for Offshore Platform

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Abstract

Dry-type transformer is the key hub equipment connecting power generation platform and power consumption platform in marine power system. Partial insulation aging caused by transformer thermal effect is one of the important factors that adversely affect the operation stability. The new ceramic insulation winding prepared by micro-arc oxidation technology has the characteristics of high thermal conductivity and high temperature resistance, and is an ideal product to replace traditional organic insulation materials. Therefore, in this paper, the thermal characteristics and overload capacity of a ceramic insulated aluminum winding dry-type transformer are studied by combining heat flow coupling simulation and experiment. By comparing the temperature field and velocity field characteristics of traditional organic insulated dry-type transformer and ceramic insulated dry-type transformer, the influence of different winding materials on transformer heat dissipation under the same load condition is studied. The hottest spot temperature of ceramic insulated winding dry-type transformer is about 86% of that of traditional organic insulated transformer. The ceramic insulated dry-type transformer has a good overload capacity. Under the premise of meeting the H-class insulation, it can carry 1.4 times the rated load. Finally, the simulation results are compared with the experimental data of the ceramic insulated dry-type transformer. The accuracy of the results was verified.
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Abstract

Dry-type transformer is the key hub equipment connecting power generation platform and power consumption platform in marine power system, so it is particularly important to ensure its safe operation. Partial insulation aging caused by transformer thermal effect is one of the important factors that adversely affect the operation stability. The new ceramic insulation winding prepared by micro-arc oxidation technology has the characteristics of high thermal conductivity and high temperature resistance, and is an ideal product to replace traditional organic insulation materials. Therefore, in this paper, the thermal characteristics and overload capacity of a ceramic insulated aluminum winding dry-type transformer are studied by combining heat flow coupling simulation and experiment. By comparing the temperature field and velocity field characteristics of traditional organic insulated dry-type transformer and ceramic insulated dry-type transformer, the influence of different winding materials on transformer heat dissipation under the same load condition is studied. On this basis, the heat dissipation structure of ceramic insulated winding dry-type transformer is studied, and the influence of different load rates on winding hot spot temperature is analyzed. The results show that the hottest spot of the ceramic insulated winding dry-type transformer winding appears in the middle and upper part of the low-voltage winding, and the hottest spot temperature rise is 146.58 K. The hottest spot temperature of ceramic insulated winding dry-type transformer is 86 % of that of traditional organic insulated transformer. The average winding temperature rise is reduced by 10% -15%. When the transverse airway width is 15 mm and the longitudinal airway width is 13 mm, the heat dissipation effect of the transformer is relatively good. Compared with before optimization, the hottest spot temperature of the dry-type transformer winding is reduced by 12.41 K. The ceramic insulated dry-type transformer has a good overload capacity. Under the premise of meeting the H-level insulation, it can carry 1.4 times the load. The simulation results are compared with the experimental data measured from a 200kVA ceramic insulated dry-type transformer test. The average temperature rise calculation error of high voltage winding is 6.9 %, and the calculation error of low voltage winding is 5.7%. The validity and accuracy of the proposed method are verified by the results.

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0 Introduction

With the rapid development of marine economy, the demand for electricity on offshore platforms is increasing. As an important equipment for energy conversion and voltage conversion, transformers are crucial to the safety and reliability of offshore power systems. Offshore platforms represented by offshore wind power [1][2], ships [3], offshore
substations [4], offshore oil drilling [5] are important application clusters of dry-type transformers. Different from the terrestrial environment, the physical space and carrying capacity of the offshore platform are limited, which puts forward higher requirements for the miniaturization and lightweight of the equipment. In addition, the high temperature, high humidity and high heat environment of the ocean requires power transformers to operate reliably at high temperatures [6]. Insulation damage and overheating fault are the main factors leading to equipment damage [7][8]. Therefore, it is of great significance to improve the operating temperature, enhance the insulation performance in salt fog environment and reduce the weight of the equipment for the application and promotion of dry-type transformers on offshore platforms. At present, system optimization and performance improvement from the perspective of transformer structure have basically reached the limit. Therefore, exploring new heat-resistant and corrosion-resistant lightweight materials will be an effective way to improve the performance of dry-type transformers.

At present, dry-type transformer windings mostly adopt organic insulation methods, such as epoxy resin [7][9][10], NOMEX paper [11][12], etc. A large number of studies have improved the thermal conductivity and heat resistance of insulation windings for transformers. The thermal conductivity of traditional organic insulating materials is low[13], usually below 0.5W/(m·K). The performance of traditional organic insulation materials limits the further improvement of the heat resistance level of dry-type transformers [14][15]. Reference [16] reviewed the application environment and material selection of dry-type transformers in marine environment. The experimental results are of scientific significance for the analysis of oil-paper insulated power transformers. Li et al. [17] studied the influence of environmental humidity and thermal aging on the insulation performance of mining dry-type transformers. In order to reduce the workload required in transformer design, Amoiralis et al. [18] proposed a method for selecting power transformer winding materials using artificial neural network (ANN). The model used provides a classification success rate of 94.7% on the test set. Brncal et al. [19] analyzed the insulation properties of transformer materials at different ambient temperatures. It can be seen that although the thermal conductivity of the transformer can be improved by organic material modification, its thermal conductivity is still lower than 0.8W/(m·K), and the long-term heat resistance level is not higher than 220°C. The thermal conductivity and heat resistance of insulation materials for transformers still need to be further improved.

The hottest spot is usually considered to be the insulation weakness of dry-type transformers, which can provide a reference for the effective monitoring of dry-type transformers [20][24]. When the hot spot temperature of the transformer winding exceeds the maximum withstand temperature of its winding insulation, the transformer winding insulation may be damaged [22-24]. This may cause the temperature of the transformer winding to rise rapidly, which seriously affects the safe and stable operation of the transformer. At present, the calculation of hot spot temperature of dry-type transformer is mainly based on empirical formula method, thermal circuit model method and finite element numerical analysis method. The finite element numerical analysis method can intuitively reflect the temperature distribution characteristics inside the transformer, and has great advantages in calculation accuracy and efficiency. Michal et al. [25] used the advanced EMAG-CFD-CFD coupling model to analyze the thermal analysis of 8.5MVA power transformer cooled by oil in ONAN mode, and used electromagnetic (EMAG) and fluid dynamics (CFD) models to study the temperature field of the transformer in detail. Xu et al. [26] used the finite volume method to simulate the two-dimensional model of the transformer under dynamic variable load, analyzed the temperature distribution of high-voltage and low-voltage windings, and pointed out that this transformer can operate under 1.2 times overload conditions. Duan [27] proposed an equivalent method of radiation-convection heat transfer at transformer boundary based on heat transfer theory, which solves the problem that the boundary is difficult to set accurately in the calculation of transformer temperature field. Reference [28] modeled the multi-winding transformer for short-circuit calculation and numerical analysis in power system. Novkovic et al. [29] proposed a dynamic thermal model of shell-type transformer and solved the nonlinear equations of heat transfer simulation. Reference [30] proposed a heat flow coupling method based on different dimensions to solve the combined model. This method considers the influence of the radiator model on the temperature distribution, which can accurately analyze the transformer temperature of the whole system and provide guidance for the transformer insulation design. Chen et al. [31] used the finite element method to calculate the thermal parameters such as heat flux and convective heat transfer coefficient, and predicted the temperature rise of dry-type transformers. Li et al. [32] established a magnetic field-flow field-temperature field coupling simulation model, predicted its potential hot spot position, and used infrared thermal imaging technology to experiment.

In order to fundamentally improve the thermal conductivity and heat dissipation capacity of the transformer windings, our research group previously proposed a new type of ceramic insulated windings with the structure of light
aluminum alloy and ceramic insulated layer. High strength aluminum alloy is used as the conductive part of the winding. Through plasma discharge oxidation technology, ceramic film was originally grown on the surface of aluminum alloy as a high thermal conductivity and high heat resistance insulation layer of winding wire. The micro-arc oxidation ceramic layer has a porous surface structure and good heat dissipation capacity.

The inorganic ceramic insulation scheme provides a new structural thinking for improving the heat resistance and thermal conductivity of dry-type transformers for offshore platforms and realizing their lightweight. Our research group has conducted a preliminary exploration on the performance of ceramic insulated aluminum wire, and optimized the withstand voltage characteristics of the ceramic layer through machine learning [33]. At present, the thermal characteristics of ceramic insulated aluminum windings transformers, and the structural analysis of the new ceramic insulated dry-type transformer are not clear. Therefore, in order to clarify the overload capacity and heat resistance of ceramic insulated winding dry-type transformer, the coupling analysis of temperature field and flow field is carried out in this paper. The effects of conduction, convection and radiation heat transfer are considered in the simulation. The effects of organic insulation materials and ceramic insulation materials on temperature rise and heat dissipation are compared. Furthermore, the influence of different heat dissipation structures on the thermal characteristics of the transformer is analyzed. The thermal characteristics of the transformer under different load rates are obtained. Based on the research above, the accuracy of the simulation results is verified by the temperature rise test of the prototype. The research results of this paper provide a reference for the hot spot analysis and insulation structure design of the new inorganic ceramic insulated winding dry-type transformer.

1. Overall structure of the transformer

1.1. Ceramic insulated dry-type transformer model

The research object of this paper is a ceramic insulated winding dry-type transformer working under natural air cooling. In the modeling process, if all the details of the transformer are considered, it will bring great difficulties to the subsequent simulation calculation. In order to improve the calculation efficiency of the model, it is necessary to simplify the model appropriately while ensuring the calculation accuracy. The three-dimensional model of the ceramic insulated dry-type transformer is shown in Fig.1. The hypothesis is as follows.

1) In the modeling process, the main components of the transformer are considered, such as iron core, insulation cylinder, high voltage windings and low voltage windings. The influence of the splint on the temperature field and magnetic field of the transformer is ignored.

2) The core is stacked by multi-layer silicon steel sheets, ignoring the influence between silicon steel sheets. High and low voltage windings are equivalent to cylinders.

3) It is assumed that the current density is uniformly distributed in the winding without considering the influence of higher harmonics.

At the bottom of the high voltage windings and low voltage windings, the triangular mesh is used to encrypt the mesh. The volume grid of the windings is formed by sweeping. For the core, this paper uses free triangular mesh. At the same time, the boundary layer is optimized by node mesh refinement. The boundary stretching factor is 1.2.

![Transformer model construction](image-url)
1.2. Ceramic insulated windings

Ceramic insulated aluminum winding has good heat dissipation performance, which breaks through the heat resistance grade of traditional organic insulated conductor. Ceramic wires were prepared by thermal electrochemical oxidation technology. The principle is to use arc discharge to enhance the chemical reaction on the anode and form a high-quality reinforced ceramic film on the surface of the aluminum wire. The thickness of the ceramic film is about 30 microns. The ceramic coating after micro-arc oxidation treatment has a strong bonding force with the aluminum matrix and is not easy to fall off. Ceramic insulated aluminum conductor and its surface structure are shown in Fig.2. Figure(a) is the real shot of ceramic aluminum wire, and figure(b) and figure(c) are the surface morphology of ceramic aluminum wire film under SEM electron microscope. The surface of the ceramic micro-arc oxidation film is loose and porous, and has a large contact area with air, which makes the film have a high thermal conductivity.

As a new type of conductive-insulating-corrosion resistant integrated functional material, aluminum alloy micro-arc oxidation ceramic material can not only avoid the problem of weak thermal conductivity of traditional organic insulating materials, but also meet the requirements of high temperature resistance and corrosion resistance of electrical equipment under special working conditions. Ceramic aluminum winding has the advantages of low density of aluminum alloy and high strength of ceramic film, which is helpful to realize miniaturization and lightweight of transformer and enhance its applicability to complex environment.

![Ceramic aluminum wire](image1)
![Surface contour](image2)
![Ceramic aluminum wire](image3)

Fig. 2. Ceramic insulated aluminum windings

2. Temperature field characteristics of the transformer

2.1. Heat dissipation principle of the transformer

The heat transfer forms of dry-type transformers mainly include heat conduction, heat convection and heat radiation. In the temperature field of dry-type transformer, conduction and convection heat transfer is the main part. The effect of radiation heat transfer is much smaller than the first two, mainly reflected in the heat transfer between non-contact solid materials. During the operation of the transformer, the windings, core and structural parts produce electromagnetic losses, which are the main heat sources of the dry-type transformer. The solid part mainly transfers heat to its surface by heat conduction, and dissipates heat to the surrounding environment. Heat is mainly transferred by convection between solid and air fluid. Due to the temperature difference between the surface of the solid material and the air medium, under the action of convective heat transfer, heat is transferred from the surface of the core and the high and low voltage windings to the gas medium to complete the heat exchange. The internal heat dissipation structure of the transformer is shown in Fig.3.
Fig. 3. Transformer heat dissipation structure

It can be seen from the diagram that the transformer has both longitudinal and transverse airway structures. There are five longitudinal heat dissipation ports, which are located between the core and the insulating cylinder, between the insulating cylinder and the windings, and between the low-voltage windings. A total of 27 transverse heat dissipation channels are distributed between the turns of high-voltage windings. The ceramic insulated dry-type transformer studied in this paper adopts natural convection cooling method, and its heat dissipation process is briefly described below.

During the operation of the transformer, temperature and gravity affect the flow state of the gas near the transformer. Cooling air enters from the bottom boundary of the transformer. When the temperature of the transformer rises, the density of the surrounding gas decreases due to heating. Under the action of buoyancy, the heated gas flows upward along the axial direction. After a certain distance of upward movement, the air will cool. Under the influence of gravity, the gas around the transformer will move downwards, forming a heat dissipation cycle process and spreading the heat continuously.

In the process of temperature field simulation, it is necessary to study the calculation process of loss. Through electromagnetic field calculation, the magnetic flux density and current of the transformer can be obtained, and then the loss of each part can be calculated. Generally, each part of the transformer is equivalent to a uniform heat source. In the process of flow field simulation, the gas state is set to laminar flow. The inlet is the velocity and temperature boundary conditions. The heat flow coupling interface is set as a non-slip wall boundary condition. When the overall temperature distribution of the dry-type transformer tends to be stable, that is, the temperature difference between the two adjacent time points is less than 1K, it can be considered that the transformer reaches a thermal equilibrium state at this time, and the temperature field and flow field distribution of the dry-type transformer can be obtained. The structure of the dry-type transformer is relatively compact, and the heat dissipation port is narrow, resulting in poor convective heat transfer efficiency. In the following, the heat dissipation structure will be optimized by changing the distance between the transverse and longitudinal airways.

2.2. Governing equations

In this section, the flow field-temperature field coupling heat transfer mechanism of dry-type transformer is analyzed, and the coupling scheme is introduced. In the process of temperature field simulation, three physical field modules of solid and fluid heat transfer, laminar flow and surface radiation are mainly used. In the solution process, the solid part is mainly the conduction equation. Due to the fluidity of air, it is necessary to solve the mass conservation and momentum conservation in the fluid domain. The solid material solution domain is mainly iron core, insulating cylinder, high voltage windings and low voltage windings. The fluid solution domain is air, set to weakly compressible form, and the temperature is 293.15 K.
When the heat generation and heat dissipation are balanced, the transformer enters a stable operation state. The governing equations under thermal equilibrium are shown in equations (1) and (2).

\[ q_x + q_y + q_f = 0 \]  
(1)

\[ \lambda A \frac{\partial T}{\partial x} + hA(T_x - T_f) + \varepsilon A h_x(T_x - T_f^x) = 0 \]  
(2)

The governing equations of solid heat transfer are as follows:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{rad} \]  
(3)

\[ q = -k \nabla T \]  
(4)

In the calculation of heat flow field, thermal insulation boundary conditions need to be added. The formula is as follows:

\[ -n \cdot q = n \cdot (k \nabla T) = 0 \]  
(5)

The transient weakly compressible flow field is selected as the fluid, and the governing equations of heat transfer are as follows:

\[ \rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + F + \varphi \nabla^2 u \]  
(6)

In the process of convective heat transfer between solid surface and fluid, the flow of fluid must follow the conservation of energy. The solution of the conservation equation is the key to accurately solve the heat flow coupling, which is used to solve the temperature rise and velocity distribution of the whole field. The governing equation of energy conservation is as follows:

\[ \rho C_p u \cdot \nabla T - S_e - \nabla (\lambda \nabla T) = 0 \]  
(7)

According to the above analysis, the fluid domain temperature can be calculated by formula (2). The velocity and pressure distribution of air fluid medium can be solved by using formulas (5) and (6). The solid temperature can be calculated by Formula (7). Considering the boundary conditions of fluid-solid coupling, the thermal-flow field coupling calculation equation is as follows:

\[ \left. \frac{\lambda A}{\partial x} \frac{\partial T}{\partial x} + hA(T_x - T_f) + \varepsilon A h_x(T_x - T_f^x) \right|_{x_i} = 0 \]  
(8)

\[ \rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + F + \varphi \nabla^2 u \]  
(8)

\[ \rho C_p u \cdot \nabla T - S_e - \nabla (\lambda \nabla T) = 0 \]

\[ -\lambda \frac{\partial T}{\partial n} = h(T_x - T_f) \]

2.3 Temperature field distribution with different winding materials

In this paper, the calculated electromagnetic loss is used as the heat source of temperature field analysis. The heat source of dry-type transformer mainly includes two parts. One is the load loss of low voltage windings and high voltage windings. The other is the no-load loss generated by magnetic hysteresis expansion.

The winding material of the ceramic insulated dry-type transformer is aluminum, and the outer layer is a ceramic insulating layer that can withstand high temperature. The effect of temperature on material properties is considered in this paper. The core loss of transformer changes with the change of magnetic flux density. The total loss of transformer core is equal to the sum of hysteresis loss, eddy current loss and additional loss. When the simulation results are stable, the effective value of core loss is 1029.7W. Compared with the measured data, the error is about 7%, which is more accurate. Finally, the total winding loss is 4310.6W, and the error is 5.4%.

In the process of temperature field calculation, the heat density per unit volume of windings and core is loaded into the physical model of dry-type transformer as heat source excitation. Through the steps of boundary condition setting, material assignment and simulation debugging, the transient solver is used to complete the simulation calculation iteratively. The temperature field distribution of the ceramic insulated dry-type transformer is shown in Fig.4.
The temperature field distribution of each component of the transformer is shown in Figure 6. It can be seen from the diagram that the hot spot temperature of the low-voltage windings is higher than that of the high-voltage windings, and the temperature of the core and the insulation cylinder is low. This is because the low-voltage windings is located between the core and the high-voltage windings, the air convection effect is not good, coupled with the blocking of the insulating cylinder, the heat dissipation is poor. At the same time, the loss of low voltage windings is higher than that of high voltage windings, which makes the temperature rise of low voltage windings higher. The high-voltage windings is located on the outermost side of the model, and the heat exchange effect with air is better. The heat dissipation area of the core is larger, the convection and radiation effects are stronger, and the temperature is lower than that of the windings. As a non-heat source, the temperature distribution of the insulation cylinder is mainly affected by the surrounding windings and iron cores. The bottom temperature is low and the temperature gradually increases along the axial direction.

In Fig.5, it shows the two-dimensional temperature rise distribution of ceramic insulated dry-type transformer and NOMEX paper insulated dry-type transformer under the same boundary conditions. From the cloud diagram, it can be seen that the high temperature area of the dry-type transformer of the two insulation methods is located in the upper part of the windings, and the temperature field distribution of the low-voltage windings and the high-voltage windings is closely related to the axial height.
insulation transformer more clearly, the temperature rise distribution curve is intercepted along path 1, path 2 and path 3, and the path diagram is shown in Fig.6. Path 1 is located in the middle of the high voltage windings, and paths 2 and 3 are located in the central axis of the low voltage windings respectively. Fig.7(a) is a schematic diagram of the axial distribution of high-voltage windings temperature rise, and fig.7(b) is a schematic diagram of the distribution of low-voltage windings temperature rise along path 2 and path 3.

![Fig.6. Schematic diagram of the path](image)

![Fig.7. Temperature rise axial distribution of transformer windings](image)

For the ceramic insulated transformer, the hottest temperature of the windings appears at the 25th turn of the first layer of the low-voltage windings. The hottest temperature of the whole transformer is 419.73K, and the temperature rise is 146.58K. The hottest spot temperature of the high-voltage windings appears on the 22nd turn of the high-voltage windings. The hottest temperature of the high-voltage windings is 416.57K, and the temperature rise is 143.42K. For NOMEX paper insulation transformer, the location of the hottest spot temperature is the same as that of the ceramic insulation. The hottest spot temperature of the whole transformer is 436.46 K, and the temperature rise is 163.31K. The hottest spot temperature of the high-voltage windings appears on the 24th turn of
the high-voltage windings. The hottest temperature of the high-voltage windings is 426.26K, and the temperature rise is 153.11K. The hottest spot temperature of ceramic insulated winding dry-type transformer is 86% of that of traditional organic insulated transformer. The average winding temperature rise is reduced by 10% -15%.

It can be clearly seen that under the same heat source conditions, the area of the hottest spot temperature of the transformer using NOMEX paper insulation is larger than that of the ceramic insulation. This is due to the high thermal conductivity of ceramic materials, which is an order of magnitude higher than the traditional organic insulation for transformers. Also, it has better heat dissipation performance. The thermal conductivity of NOMEX insulation paper is small, the heat conduction per unit area is less, and the heat is not easy to dissipate compared with ceramic insulation, which makes the windings temperature higher. At the same time, this paper selects five sections of L1, L2, L3, L4 and L5 to compare the distribution of transverse temperature rise of dry-type transformers with two insulation methods. The temperature rise distribution is shown in Fig. 8.

In Fig. 8, the L1 path reflects the lateral distribution trend of the temperature rise at the bottom of the dry-type transformer. The position of X = 60mm is the right boundary of the transformer core. In the range of [0, 60mm], the temperature rise of ceramic transformer and NOMEX paper transformer is approximately the same, about 82.41 K. In the [60, 160mm] interval, the temperature rise difference between the two is not large, because the region mainly relies on the core heat source to exchange heat with the surrounding air medium. The core heat source is small and has little effect on the surrounding air medium.

![Fig. 8. Temperature rise distribution curve](image)

From the L2 and L3 curves, it can be seen that in the [60, 180mm] interval, the temperature rise distribution curves of the two insulation dry-type transformers show a clear peak-valley change trend. The peak is the temperature rise of the insulation windings, and the bottom position is the temperature rise between the windings or between the windings and the core. As the main heat source of the dry-type transformer, the temperature rise of the transformer windings is higher than that in the airway. There are two peaks in the L2 temperature rise curve, and the first peak is higher than the second peak. The reason is that the heat dissipation condition of the low voltage windings is poor, and the temperature rise is slightly higher than that of the high voltage windings. The temperature rise at the middle point of the windings is slightly higher than that on both sides. This is because the middle point is in the middle layer of the same windings, which is relatively poor with the surrounding heat dissipation, resulting in
an increase in the temperature rise value. In the temperature rise curve drawn along the L2 path, the maximum temperature rise peak-valley difference of the ceramic insulated dry-type transformer is 7.5K, and the maximum temperature rise peak-valley difference of the NOMEX paper insulated dry-type transformer is 22.6K. It can be seen that the temperature rise curve of ceramic insulation is more smooth-out than that of NOMEX paper insulation. Due to the large thermal conductivity of the ceramic, the heat is easier to dissipate, which makes the temperature difference decrease.

Comparing the curves of the two insulation methods, it can be seen that the curves are basically the same in the core area. In the [60,180mm] region, the temperature rise of NOMEX paper-insulated transformer is higher than that of ceramic-insulated dry-type transformer. The peak temperature rise of the ceramic transformer is 127.18 K, and the peak temperature rise of the NOMEX paper insulation transformer is 147.20 K, which is decreased by about 13.6 %. Comparing the temperature rise at the trough position of the curve, the temperature rise at the trough of the ceramic transformer is 119.69 K, and the NOMEX paper insulation transformer is 124.69 K, which is reduced by about 4%. According to the analysis, the thermal conductivity of the ceramic insulation windings is better. It can reduce the peak valley difference of the curve, and is more conducive to the diffusion of heat to the air medium. In the temperature rise curve drawn along the L3 path, the change trend of the temperature rise curve of the ceramic insulation transformer windings and the NOMEX paper insulation transformer windings is approximately the same, and there are two peaks. The peak-valley temperature difference of the ceramic insulation transformer windings is 3.8K, and the peak-valley temperature difference of the NOMEX paper insulation transformer windings is 6.2K. The L4 path is the cut line at Y = 160mm. It can be seen from the figure that the difference between the temperature rise curve of the ceramic transformer and the NOMEX paper transformer mainly exists in the interval [90, 180mm]. In this interval, the temperature rise curve shows a downward trend, and the temperature rise of the ceramic transformer is about 19K lower than that of the NOMEX paper transformer. From the L5 temperature rise path curve, it can be seen that the temperature rise curves of the two are approximately the same. In the [90,150mm] interval, the temperature rise of the ceramic transformer is slightly lower than that of the NOMEX paper transformer, and the maximum temperature rise difference is about 3.1K. The curves increase gradually first, and then the temperature rise decreases steadily until the temperature rise of the environmental medium is reached.

3. Velocity field analysis

The flow field distribution in the airway of ceramic insulated transformer is shown in Fig.9. It can be seen from the diagram that in the case of natural convection heat transfer, the flow field distribution of ceramic insulated dry-type transformer is not uniform. Figures (a) and (b) are the velocity field distribution of the airway. Figures (c), (d) and (e) are the velocity distribution vectors of the longitudinal airway, the end of the transformer and the transverse airway, respectively, to analyze the influence of air medium flow inside the transformer airway. Due to the thermal expansion of the gas, the density difference is generated, forming an air cooling cycle. It can be seen from the diagram that the velocity distribution is not uniform, and the maximum velocity is 1.6m/s at the end. The bottom velocity of dry-type transformer is low. The maximum flow velocity in the longitudinal airway was 1.186m/s, which appeared at the upper outlet of the longitudinal airway. The air velocity in the transverse airway is small, about 0.1-0.3m/s. In the velocity vector diagram, the overall trend is from bottom to top.

In the longitudinal airway, the velocity vector direction is from bottom to top, which is in line with the actual working state. The flow rate of the transverse airway is mostly from right to left. This is because the left side of the transverse airway is the heat source distribution area, and the air is heated to make the pressure on the left side smaller, forming a pressure difference, so the air velocity vector in the transverse airway flows from left to right.
In order to study the relationship between the temperature distribution of the transformer and the flow rate between the airways, this paper draws the distribution curve of the relationship between the flow rate and the temperature between the airways of the ceramic transformer in the interval of [60,160mm]. The point interval is 0.5mm, and the results are shown in Fig.10. In the airway, the airflow velocity is the largest at the center of the airway and gradually decreases to zero at both ends. It can be seen that the flow velocity of the airway medium inside the windings is low, and the flow velocity between the windings and the core and between the windings and the shell is high. In the range of [60,80mm], it belongs to the airway between the core and the insulating cylinder, and the flow rate increases first and then decreases. From the diagram, the maximum flow velocity in the longitudinal airway appears at X=72mm, and the maximum flow velocity is 1.17m/s. In the range of [84,104mm], it is the airway between the insulating cylinder and the first layer of the low-voltage windings, and the flow rate increases first and then decreases. It can be seen that the maximum flow rate in the airway appears at X = 95mm, and the maximum flow rate is 1.10m/s. In the range of [106,116mm], it is the longitudinal airway between the low voltage windings of the transformer. Due to the narrow width of the airway, the heat dissipation condition is worse than other airways, so the flow rate of the airway is small. The maximum velocity appears at X = 112mm, and the maximum velocity is 0.25m/s. In the range of [119, 139mm], is the airway between the second layer of the low-voltage windings and the right insulating cylinder. In the [140,160mm] interval, the fifth peak of the velocity distribution curve appears. This interval is the heat dissipation airway between the insulating cylinder and the high voltage windings. When X = 150mm, the maximum velocity is 0.934m/s. In the range of [161,194mm], it is the flow velocity in the transverse airway between high-voltage windings, and the air flow velocity is small, between 0.1~0.3m/s. In the range of [195,300mm], the velocity increases rapidly to the maximum velocity of 1.125m/s, and then gradually decreases.
It can be seen that in the [60,104mm] interval, the temperature of the transformer is on the rise. This interval is located between the core and the low-voltage windings, and there are two airways, so there are two peaks in the velocity distribution. The contribution of the windings to the temperature is greater than that of the core. The insulation cylinder does not provide heat source. There is a position interval with a large flow velocity in this area. However, the relative position of the windings heat source plays a major role. Therefore, the closer to the low-voltage windings, the higher the temperature, showing a significant upward trend. The low voltage windings is located in the range of [105,120mm]. The maximum temperature is 400.18K, and the average temperature is 397.25K. Due to the narrow longitudinal airway, the flow rate is significantly lower than that of the surrounding airway, which makes the heat loss slower and the temperature in the airway higher. In the range of [120, 140mm], the temperature decreases gradually, and the lowest temperature is 380.25K at X = 140mm. In the [140,190mm] interval, the temperature increases first, and the temperature remains basically unchanged after reaching the inflection point X = 160mm. This interval is the area where the high voltage windings is located, and the final temperature is stable at 389.89 K. In the [190,300mm] interval, with the increase of the interval value, the distance from the heat source is farther and farther, the temperature gradually decreases, and finally stabilizes at about 301K.

4. The airway structure optimization

4.1. Longitudinal airway structure analysis

It can be seen from the above that the vertical airway between the low-voltage windings of the dry-type transformer model in this paper is relatively narrow. At the same time, the flow rate in the transverse airway is also small. The width of the transformer airway can be reasonably designed to make the heat dissipation effect better and effectively reduce the temperature rise of the windings. The initial width of the longitudinal airway of the transformer is 12 mm, and the initial width of the transverse airway is 16 mm. In this section, by changing the width of the vertical airway and the height of the transverse airway, the influence of the temperature field distribution of the windings is analyzed, and the reasonable airway width is finally obtained. The longitudinal airway width d is set to 8mm, 10mm, 12mm, 14mm, 16mm and 18mm respectively to study the influence of changing the longitudinal airway width on the temperature field distribution of the windings. The temperature distribution cloud diagram of transformer windings under different longitudinal airway widths is shown in Fig.11.
It can be seen that with the increase of the vertical airway width $d$, the temperature of the hottest area of windings decreases. When the width $d$ is 8mm, 10mm, 12mm, 14mm, 16mm and 18mm respectively, the hottest temperature of the windings is 424.82K, 421.33K, 417.13K, 412.22K, 410.68K and 408.82K. The width of the vertical airway has a great influence on the temperature distribution of the winding wire cake. The transverse distribution of temperature rise and flow velocity at the $Y = 0$ position is shown in Fig.12. It can be seen that the longitudinal airway change has little effect on the flow rate and temperature rise in the airway at the central axis. The change of longitudinal airway mainly affects the temperature rise and velocity distribution at the top outlet of the transformer. Fig.13 shows the velocity distribution of $d=8$mm, 12mm and 16mm. It can be seen that with the increase of the airway width, the flow velocity at the top outlet of the transformer decreases, which is more conducive to the heat dissipation of the transformer windings. The flow direction in the longitudinal airway is from bottom to top. When $d=8$mm, the maximum flow velocity in the longitudinal airway is 1.6m/s; when $d=12$mm, the maximum flow velocity in the longitudinal airway is 1.42m/s; when $d=16$mm, the maximum flow velocity in the longitudinal airway is 1.24m/s.
In order to better study the trend of the maximum and minimum temperature of the winding with the change of the longitudinal airway width $d$, this paper draws the curve of the winding temperature, as shown in Figure 14. It can be seen from the figure that as the longitudinal airway width $d$ increases, the maximum temperature and minimum temperature of the transformer winding will decrease, and the trend will gradually slow down. For the maximum temperature of the winding, the change rate is about 2.25K/mm in the range of $[8,14]$mm. In the $[14,18]$mm interval, the decline rate slowed down, and the change rate was about 1.5K/mm. For the minimum temperature of the winding, the change rate is about 5.9K/mm in the range of $[8,12]$mm. In the $[12,18]$mm interval, the decline rate slowed down, and the change rate was about 1.2K/mm. It can be seen that in the interval of $[12,14]$mm, the maximum temperature drop rate of transformer winding is larger, and changing the airway width $d$ has a better effect on reducing the temperature of the hottest spot of winding. Compared with the initial width, $d=12$mm~14mm is more suitable.

4.2. Transverse airway structure analysis

Fig.15 is the windings temperature field distribution cloud diagram after changing the height of the transverse port $h$ of the transformer. The height of the airway $h$ is set to 12 mm, 14 mm, 16 mm and 18 mm respectively. When the airway height $h$ is 12mm, 14mm, 16mm and 18mm, the hottest temperature of the windings is 437.86K, 432.17K, 417.13K and 415.32K respectively. When $h=12$mm, the highest windings temperature appears at the top of the high-voltage windings. The lowest temperature appears at the top of the low voltage windings. The heat dissipation condition at the top of the low voltage windings is better, so the temperature is lower than that of the high voltage windings. It has faster heat exchange and lower temperature. When $h=14$mm, the highest temperature of the windings appears at the top of the high voltage windings. The lowest temperature appears at the top of the low-
voltage windings. When $h=16\text{mm}$, the highest temperature of the windings appears at the top of the low-voltage windings, and the highest temperature is $417.13\text{K}$. The lowest temperature of the windings appears at the bottom of the high voltage windings, and the lowest temperature is $388.56\text{K}$. When $h=18\text{mm}$, the highest temperature of the windings appears at the top of the low-voltage windings. The lowest temperature appears at the bottom of the high voltage windings.

The flow velocity cloud map is shown in Fig.16. It can be seen that the transverse airway change has a great impact on the flow rate at the top of the transformer. With the increase of width, the air flow rate at the top of the transformer decreases.

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**Fig. 15. Cloud diagram of windings temperature changing with $h$**

**Fig. 16. Velocity distribution cloud**
In order to better study the trend of the maximum and minimum temperature of the winding with the change of the longitudinal airway width \(d\), this paper draws the curve of the winding temperature, as shown in Figure 17. As the airway width \(h\) increases, the maximum temperature and minimum temperature of the windings gradually decrease. For the maximum temperature of the windings, the temperature change rate is 2.85K/mm in the range of [12,14mm]. In the [14,16mm] interval, the change rate is 7.52K/mm. When \(h>16\)mm, the temperature change rate becomes smaller, about 0.91K/mm. Through analysis, it can be seen that considering the cost and volume, the horizontal airway in the [14,16mm] interval is more suitable for the transformer model in this paper.

![Figure 17. The curve of temperature rise versus \(h\)](image17)

According to the above analysis, the width of the longitudinal airway \(d\) is more suitable between [12,14mm], the width of the transverse airway \(h\) is more suitable between [14,16mm], and the effect of changing the airway structure is better in this interval. Finally, the temperature rise distribution of the transformer is shown in Fig.18.

It can be seen from the figure that by selecting a reasonable airway width, the temperature difference between the top and bottom of the transformer windings is reduced, and the temperature distribution is more uniform. After optimization, the hottest spot temperature of the ceramic insulated dry-type transformer is 407.32 K, which appears in the middle and upper part of the low-voltage windings. The hottest spot temperature of the high voltage windings is 403.14 K. Compared with before optimization, the overall hottest spot temperature of the transformer is reduced by 12.41 K, and the hottest spot temperature of the high voltage windings is reduced by 13.43 K.

![Figure 18. Temperature distribution diagram](image18)
5. Research on overload capacity

In order to ensure the normal service life of the transformer, the transformer is generally operated under the rated load. However, with the increase of electricity consumption, the overload of transformers must be considered, allowing transformers to have certain overload capacity on the basis of ensuring service life. Hot spot temperature is an important factor limiting the overload capacity of dry-type transformers. In this section, by changing the load rate of the dry-type transformer with ceramic insulation windings, the relationship between the hot spot temperature of the transformer windings and the load rate is studied, and then the overload capacity of the dry-type transformer is studied. The temperature field analysis of the transformer is carried out when the load rate multiple is 0.4, 0.6, 0.8, 1, 1.2 and 1.4 respectively. Finally, the temperature field distribution under different load conditions is obtained as shown in Fig.19.

![Fig.19. Windings temperature distribution under different load rates](image)

According to the simulation results, this paper draws the curves of the hottest spot temperature rise of the ceramic dry-type transformer winding, the average temperature rise of the high and low voltage winding, the maximum temperature difference of the high and low voltage winding and the maximum flow rate in the airway under different load rates. As shown in Figure 20.

![Fig. 20. Parameter variation curves under different load rates](image)
With the increase of load rate, the temperature difference between high and low voltage windings gradually increases. When the rated load, the temperature difference of high voltage windings is 27.23 K, the temperature difference of low voltage windings is 23.58 K; when the load is 1.4 times, the temperature difference of the high voltage windings increases to 32.19 K, and the temperature difference of the low voltage windings increases to 29.20 K. The average temperature rise of high and low voltage windings also increases with the increase of load rate, which is positively correlated with the change of flow velocity in the airway. It can be seen that under the same load rate, the average temperature rise of high and low voltage windings is not much different. At the rated load, the maximum flow velocity in the airway was 1.35 m/s; at 1.4 times the load, the maximum flow rate in the airway is 1.63 m/s. The insulation grade of dry-type transformer refers to the heat resistance grade of the insulation material used in the transformer winding. The grades of insulation materials commonly used in transformers are A, E, B, F and H. Each insulation grade of insulation material has a corresponding limit allowable working temperature. If the temperature of the hottest spot of the transformer winding exceeds the specified maximum allowable temperature, it will cause accelerated aging of the insulation material and shorten the life of the transformer. If the temperature exceeds the allowable value a lot, the insulation will be damaged, resulting in transformer burning.

The transformer can withstand 1.4 times overload under the condition of meeting the H-level insulation requirements. Fig. 21 shows the distribution of transformer temperature along the transverse coordinate under different load rates, and the path is L1-L5. It can be seen that along the axial direction, the temperature difference between the transformer windings and the airway gradually decreases. This is because the top convection heat transfer effect is better, the heat is easier to dissipate, so that the temperature difference is reduced. As shown in the figure, in the low-voltage windings area, the temperature reaches the first peak. The temperature of the windings is obviously higher than that between the airways.

Fig. 21. Parameter variation curves under different load rates
6. Prototype test and verification

In this paper, the simulation data of ceramic windings dry-type transformer are fitted and calculated, and compared with the measured average temperature rise data obtained by the specially constructed experimental system. The transformer prototype is shown in Fig.22. Ceramic insulated aluminum conductor breaks through the heat resistance grade of traditional organic insulated conductor, with large thermal conductivity and improved mechanical strength.

![Transformer prototype diagram](image)

The research object of this paper is a 200KVA three-phase dry-type transformer, working in the AN cooling regime as showed in Fig.1. The windings of the low voltage side adopts the layer windings, and the windings of the high voltage side is the pancake windings. Dry-type transformer is mainly composed of iron core, high voltage winding, low voltage winding, insulating cylinder and clamp. The transformer winding is made of new micro-arc oxidation ceramic wire. The size of transformer core is $880cm(x) \times 124.25cm(y) \times 960cm(z)$. The high-voltage winding is on the outside, with an outer diameter of 392cm and an inner diameter of 318cm. The low-voltage winding is located inside and is divided into two layers. The outer diameter of the first layer is 216cm and the inner diameter is 208cm. The outer diameter of the second layer is 240cm and the inner diameter is 232cm. The coil and core along the x coordinate are marked as a phase, b phase and c phase respectively. The phase difference between adjacent coils is 120°. The main parameters of the transformer are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage HV</td>
<td>6000V</td>
</tr>
<tr>
<td>Rated voltage LV</td>
<td>400V</td>
</tr>
<tr>
<td>Type of cooling</td>
<td>AN</td>
</tr>
<tr>
<td>Connection symbol</td>
<td>Yy0</td>
</tr>
<tr>
<td>Rated current HV</td>
<td>19.2A</td>
</tr>
<tr>
<td>Rated current LV</td>
<td>288.7A</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

Fig.23 are the fitting function and variance of the temperature rise data of high voltage windings and low voltage windings under the working conditions of 19.2 A rated current and 293.15 K ambient temperature. Under the condition of 95 % prediction band, the fitting curves of high voltage windings temperature rise and low voltage windings temperature rise can be approximately expressed by quadratic function curve, and the error is small. It can be seen from the diagram that the temperature rise of the windings increases first and then decreases with the increase of the axial height, and the peak value is located in the middle and upper parts.
7. Conclusion

In this paper, a temperature field model of ceramic insulated dry-type transformer is established to study the temperature field characteristics of ceramic windings. Through the magnetic field simulation, the loss of the core and windings during the rated operation of the transformer is obtained, and it is used as the heat source to load the temperature field model of the transformer in the form of heat rate for finite element coupling calculation. Finally, the temperature and flow field distribution of the ceramic dry-type transformer are obtained.

The specific conclusions are as follows.

(1) The temperature of low voltage windings is higher than that of core and high voltage windings. The most hot spot temperature rise appears in the middle and upper part of the low voltage windings; the temperature of low voltage windings and high voltage windings increases first and then decreases slightly along the axial height. Therefore, in the design of the transformer, the temperature rise of the upper end area of the transformer windings should be emphatically considered to prevent the problem of local overheating and affect the ceramic insulation performance.

(2) The hottest spot temperature of ceramic insulated winding dry-type transformer is 86 % of that of traditional organic insulated transformer. The average winding temperature rise is reduced by 10%-15%. The velocity field distribution of the transformer is uneven, and the maximum velocity of the transformer appears at the top of the airway. The maximum flow velocity in the longitudinal airway was 1.186m/s, which appeared at the upper outlet of the longitudinal airway. The air velocity in the transverse airway is small, about 0.1~0.3m/s.

(3) The optimization analysis of the airway shows that the most suitable longitudinal airway width d should be selected between 12 mm and 14 mm, and the transverse airway D should be selected between 14 mm and 16 mm. In this paper, a transformer model with a longitudinal airway width of 13 mm and a transverse airway width of 15 mm is selected for simulation calculation. The overall hottest spot temperature of the transformer is reduced by 12.41 K.

(4) In this paper, a ceramic insulated dry-type transformer prototype was developed and a temperature rise test was performed. The ceramic insulated dry-type transformer can withstand 1.4 times overload and meet the requirements of H-grade insulation. The accuracy of the model is verified by comparing the simulation results with the actual temperature rise of the ceramic dry-type transformer. The average temperature rise calculation error of the high voltage winding is 6.9 %, and the average temperature rise calculation error of the low voltage winding is 5.7 %.

The ceramic insulated winding dry-type transformer studied in this paper can be used as a way to realize the next generation of high-performance marine transformers.

Acknowledgements

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