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Temperature Rise Comparison of Switchgear in SF_6, N_2, and Air

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Abstract

Based on the heat conduction equation, fluid flow governing equation and radiation heat transfer equation, a multi-physics coupled mathematical model is established, the convection heat transfer problem between solid and fluid is solved by wall function. The three dimensional thermal field in a type of switchgear filled respectively with SF6, N2, and air are calculated and analyzed to discuss the feasibility of using air or N2 as the substitution of SF6 by the finite volume method. The results show that the temperature fields in three gases are similar in the switchgear. The temperature rise of current-carrying loop is the highest in SF6 and is the lowest in the air. So the conclusion could be made that air or N2 can replace SF6 as the insulating gas of switchgear on the perspective of temperature rise.

Keywords: *temperature rise, switchgear, SF_6, N_2, air*

1. Introduction

Gas insulation technology has been generally applied in medium voltage switchgear for its enhancement of reliability and diminution of floor area of switchgear. Due to the admirable insulating property, SF_6 becomes the most frequently used insulating gas in switchgear. However, SF_6 is greenhouse gas, so decreasing and even forbidding the use of SF_6 is surely to be the trend in the development of switchgear [1]. Air and N_2 are both inexpensive and environmental, so it is significative of making air and N_2 as the substitution of SF_6 in switchgear. A lot of research about searching the substitution of SF_6 has been carried out both domestic and overseas. Reference [2] discusses the breakdown property to explore the feasibility of using N_2 and mixture of N_2 and SF_6 as the substitution of SF_6. Reference [3] discusses the insulation property of N_2 or C_4F_8, to find out whether they could be the substitution of SF_6.

Temperature rise directly reflects the safety performance of switchgear, so it is one of the significant factors of analyzing the feasibility of substitution of SF_6. However, references based on the perspective of temperature rise of searching the substitution gas of SF_6 are rarely to be seen.

Heating and dissipating process is a complicate physical process combines conduction, convection and radiation, and it could be analyzed by mathematical modeling and numerical calculation. However, it is difficult to carry out this calculation because of the complicate 3D model of the switchgear and the large grid numbers in numeric calculation.

In this paper, based on the heat conduction equation, fluid flow governing equation and radiation heat transfer equation, the multi-physics coupled mathematical model is established, and wall function is used to solve the convection heat transfer problem between the solid and the gas. After the simulation and calculation of the thermal field respectively in SF_6, N_2 and air, the 3D distribution of thermal field respectively in three gases has been obtained. Then comparison and analysis of the calculating results has been done to discuss the feasibility of using N_2 and air as the substitution of SF_6 on the basis of temperature rise.

2. Mathematical Model [4]

The generation of heat in switchgear is caused by heat loss of resistances. The heat transferred in the conductors is mainly by conduction. Heat transfers from conductors to the gas

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by convection and radiation, and finally transfers to the ambient air outside the switchgear through the enclosure.

2.1. Thermal Governing Equations

The k-ε turbulence model is introduced in the heat transfer and fluid flow, including the mass, momentum, energy conservation equations, k equation and ε equation. The governing equations can be written in conservation form [5] as follows equation (1). So the variables of velocity, temperature, k and ε can be solved using the numerical method.

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho V\phi) = div(\Gamma grad\phi) + S \tag{1}$$

Where ϕ is the universal variable which is expressed as temperature, velocity, pressure, k and ε respectively; *V* is the velocity vector; Γ is the coefficient of diffusion; *S* is the sources, which include the Joule's loss and radiation heat flux from the conductor to the enclosure.

The Joule's loss is expressed by the following equation:

$$\Phi = I^2 R \cdot \tag{2}$$

Where Φ is the Joule's loss, *I* is the current, *R* is the resistance.

In the switchgear, the radiation from the conductor to the enclosure is caused by the temperature difference between the conductor surface and the enclosure. The heat transfer by radiation is calculated by Stefan-Boltzman's law as follows.

$$\Phi = \sigma\xi A_1 (T_1^4 - T_2^4)\,. \tag{3}$$

Where T_1 and T_2 are the conductor surface temperature and enclosure temperature respectively, A_1 is the conductor surface area, ξ is the conductor emissivity constant [6], σ is the Stefan-Boltzman constant, Φ is the radiation heat flux.

2.2. Boundary Conditions

Generally, wall function and the low Re (Reynolds number) k-ε turbulence model and the convection heat transfer coefficient can be applied to deal with the solid-fluid boundary conditions [7]. Compared with the low Re model which needs increasing the grid density, wall function can reduce the grids in SF_6 gas adjacent to the conductors, so CPU times and memory storage can be saved more in computer [8, 9]. The initial temperature of the conductors and the enclosure must be assumed firstly if using the convection heat transfer coefficient [10]. However, the initial temperature can not be considered in wall function. Therefore, we introduce wall function to calculate the fluid flow and heat transfer on the solid-SF_6 gas boundary in this paper.

In wall function, the dimensionless variables of velocity u^+, distance y^+ and temperature T^+ are respectively defined by the following equations:

$$u^+ = \frac{u}{\sqrt{\tau_w / \rho}}\,. \tag{4}$$

$$y^+ = \frac{\Delta y}{v}\sqrt{\frac{\tau_w}{\rho}}\,. \tag{5}$$

$$T^+ = \frac{(T - T_W)(c_\mu^{1/4} k^{1/2})}{q_W / \rho c_p}\,. \tag{6}$$

Wall function assumes a logarithmic boundary layer adjacent the conductors, in which the u^+ and T^+ satisfy the basic logarithmic equations. So the wall shear stress τ_w and the heat flux q_w from wall given by following equations (7) and (8) are related to SF_6 gas flow through the logarithmic equations.

$$\tau_w = \eta_t \frac{u_P - u_W}{y_P} . \tag{7}$$

$$q_W = \lambda_t \frac{T_P - T_W}{y_P} . \tag{8}$$

Where T_W, T_P and u_w, u_p are the temperature and the velocity on wall and in the gas respectively; ρ is the fluid density; c_p is the specific heat at constant pressure; v is the kinematic viscosity; c□is the turbulent model constant; η_t is the turbulent viscosity; λ_t is the turbulent heat conductivity.

Consequently, q_w can be obtained according to the equations (4)-(8). And η_t and λ_t can be expressed as follows equations (9)-(10).

$$\eta_t = \frac{y_p^+}{u_p^+} \eta . \tag{9}$$

$$\lambda_t = \frac{y_p^+}{T_p^+} \sigma_L \lambda . \tag{10}$$

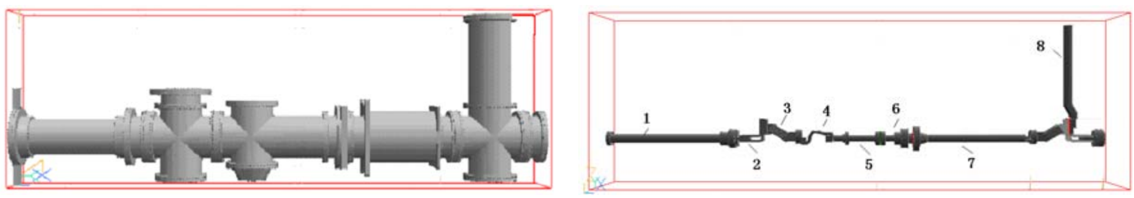
Whereσ_L is the Prandtl number; λ is the gas heat conductivity; η is the dynamic viscosity.

3. Simulation Computation

3.1. Geometry Model of the Switchgear

The main components of the switchgear are bus bar, circuit breaker, current transformer, and a three-position isolation switch. The switchgear has three phases, and each phase is coordinate with each other. The bus bar and three-position isolation switch are located in the lower part of the cylinder, circuit breaker and current transformer are located in the upper part of the cylinder, and the cable wire is extracted on the top of the cylinder. The rate current of the switchgear is 2000A, rate voltage is 40.5kV, and the frequency is 50Hz.

Each phase of the switchgear is independent with each other, and they share the same structure, so one phase could on behalf of the other two during the calculation. In this paper, the middle phase is the study object. Its model and components in current-carrying loop are as shown in Figure 1. The enclosure is defined as the calculation domain boundaries, and it has been set as ambient temperature.



(a) The external geometric model (b) Components in the current-carrying loop

Note: 1-conducting rod1, 2-conducting plate, 3-contact finger, 4-conducting band, 5-movable conducting pole, 6-fixed conducting pole, 7-conducting rod2, 8-external bus

Figure 1. The model of switchgear

3.2. Parameter and Initial Conditions

According to the Thompson theory [11], increasing the gas pressure could considerably improve the insulating ability of the insulating gas in the switchgear. The insulating ability of N_2 and air is approximately 1/3 of the one of SF_6 at the same pressure. So in order to make sure the three gases has the same insulating ability, and under the premise of low gas pressure in the switchgear, the initial pressure of N_2 and air is 0.25MPa, and the initial pressure of SF_6 is 0.08MPa in this paper. The initial temperatures of the three gases are all 20□. Their thermodynamic parameters can refer to reference [12].

The material of the conductors in the current-carrying loop, bushings and enclosure are copper, epoxy resin and steel respectively. Their thermodynamic parameters can refer to references [12, 13].

Consider the skin coefficient of every conductor, the final calorific value of every conductor is the product of Joule's loss and relevant skin coefficient. The power of major components of current-carrying loop at 20℃ is listed in Table1.

3.3. Grids

The hexahedral grid is used in the numerical calculation, and the total grids reach 1.2×10^6 in the cabinet. The grids are as shown in Figure 2.

Table 1. Power loss of components(20℃)

component	Power(W)
conducting rod1	34.2
conducting rod2	43.8
conducting band	48.3
movable conducting pole	32.7
fixed conducting pole	33.2
external bus	36.0

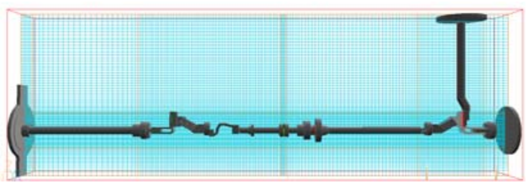
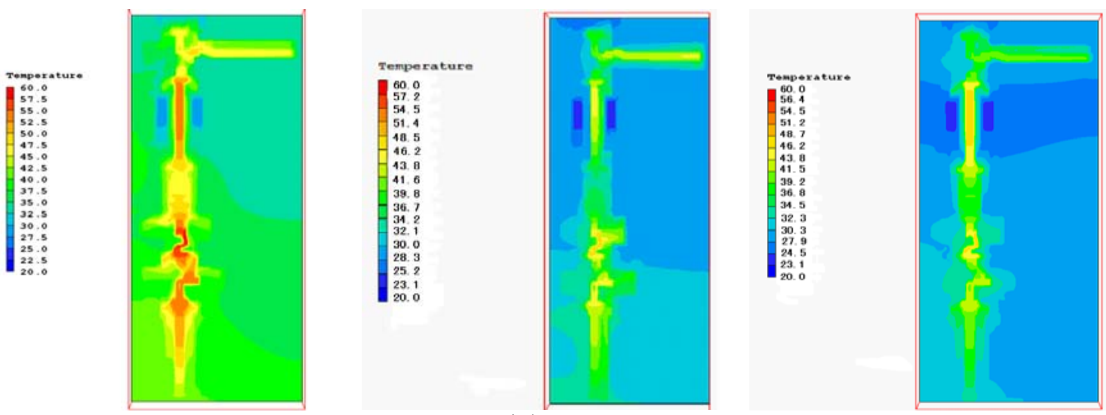


Figure 2. The mesh of numerical calculation

3.4. Results and Analysis of Numerical Calculation

3.4.1. Thermal Field

The temperature distribution in three gases is as shown in Figure 3.



(a) SF_6 (b) N_2 (c) air

Figure 3. Temperature field of switchgear in three gases

The reasons caused differences of temperature are the diversity of resistance values, the size of the conductors, and the conditions of air flow. Conductor which own a lower resistance value and a larger size, gets a lower temperature; on the contrary, it gets a higher temperature. Like the conducting band in Figure 3, it has a high resistance value and a small size compared with other conductors in the current-carrying loop, so it gets a higher temperature. Hot gas flows upwardly, so the upper part of the current-carrying loop's temperature is higher than one of the lower part.

3.4.2. Comparison and Analysis of Temperature Rise in the Three Gases

Draw the temperature values in three gases into curves, as shown in Figure 4. In Figure 4, X-axis is components numbers (the order is numbered from lower part to the upper part of the current-carrying loop), Y-axis is the ratio of components' temperature to the initial temperature.

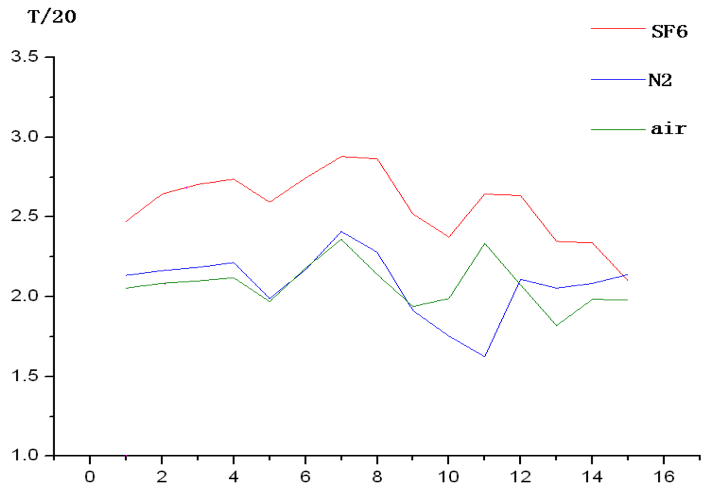


Figure 4. The temperature of current carrying conductor in three gases

It could be seen from Figure 4 that the temperature distributions of the three gases are similar. The temperature rise in SF_6 is the highest, and is the lowest in air.

The quantity of heat transferred from the conductors to the gas in the three different gases is supposed to be the same, so the only parameter that affects the gas diffusion ability is thermal diffusivity. The gas diffusion ability gets better with the thermal diffusivity growing larger, so the heat produced by the current-carrying loop could diffuse more rapidly. Thus insulating gas with a higher thermal diffusivity has a lower temperature rise in the current-carrying loop. It could be concluded that, under the premise of ceteris paribus, temperature rise turns lower when gas gets a higher thermal diffusivity.

The expression of thermal diffusivity is $a = \lambda / (c_p \rho)$, where α is the thermal diffusivity, λ is the thermal conductivity, c_p is the specific heat capacity of gas, ρ is the density. After calculation, the sequence of the three thermal diffusivities is $\alpha_{air} > \alpha_{N_2} > \alpha_{SF_6}$ .So temperature rise of current-carrying loop in SF_6 is the highest; one in air is the lowest. In summary, from the perspective of temperature rise, using N_2 and air as the substitution of SF_6 is feasible.

4. Conclusion

In this paper, the coupled mathematical model which involves differential equations of conduction, convection and radiation is established for calculating the thermal field of the switchgear. Wall function is used to solve the convection heat transfer problem between the solid and the gas. The finite volume method is applied to solve the differential equations for the 3D geometry model of the switchgear. The thermal field of the switchgear is simulated, and the distribution of temperature is obtained respectively in SF_6, N_2, and air. The results show that the distributions of temperature in the three gases are similar, and the temperature rise in SF_6 is the highest, and is proved to be the lowest in air. After comparing the thermal field in the switchgear respectively filled with SF_6, N_2 and air, it could be summed up that, from the perspective of temperature rise, the temperature rise in N_2 and air is lower than the one in SF_6, hence using N_2 and air as the substitution of SF_6 to be the insulating gases in switchgear is feasible.

Aknowledgement

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