Finite Element Analysis of Thermal Problems in Gas Insulated Power Apparatus with Multiple Species Transport Technique

Xiaowen Wu, Naiqiu Shu, Hongtao Li, Hui Peng and Ling Li
School of Electrical Engineering, Wuhan University, Wuhan 430072, China
whuwxw@outlook.com

***Abstract*—In this paper, multiple species transport technique is proposed to deal with the heat transfer problem of gas insulated power apparatus, in which the ambient air as well as SF_6 gas is also included in the solution region. The finite element method (FEM) is employed to investigate the coupled eddy current, fluid and thermal fields. Temperature dependent electrical and thermal material properties are considered. The convective heat transfer coefficient distribution is calculated and proved to be different along the tank surface. The proposed method is applied to the thermal analysis of both single- and three-phase bus bars and is validated by comparison with the analytical model and the experimental results reported in the literature.**

***Index Terms*—Thermal analysis, finite element method, fluid dynamics, radiation effect, analytical model.**

I. Introduction

The current-carrying capacity of power apparatus is limited by the maximum operating temperature [1]. It is therefore quite necessary to perform accurate thermal analysis in the designing process. The coupled magnetothermal finite element method (FEM) has been used extensively in the solution of thermal problems in gas insulated power apparatus [1]-[3]. In these papers, the natural convection between the conductor and the tank is equalized with heat conduction. Moreover, the nondimensional parameters that include Grashof (Gr), Prandtl (Pr) and Nusselt (Nu) numbers are employed to determine the constant convective heat transfer coefficient on the surface of the power apparatus. These methods will loss accuracy, especially when the investigated structure is complex and the thermal model is three-dimensional (3-D) [4], [5], because convective heat transfer coefficient actually depends on the surface temperature and geometry.

In this paper, eddy current, fluid and thermal fields of single- and three-phase SF_6 gas insulated bus bars are analyzed with FEM. As the ambient air is introduced into the solution region, multiple species transport technique is used to calculate the material properties of the gas mixture. Heat convection happened both inside and outside the bus bars are calculated with the theories of fluid dynamics. The results are compared with the analytical calculation and experimental results reported in the literature.

II. Finite Element Model

A. Eddy Current Field Model

The solution regions of gas insulated bus bars are given in Fig. 1. The two-dimensional (2-D) electromagnetic problem in a time-harmonic regime can be stated as follows [6]:

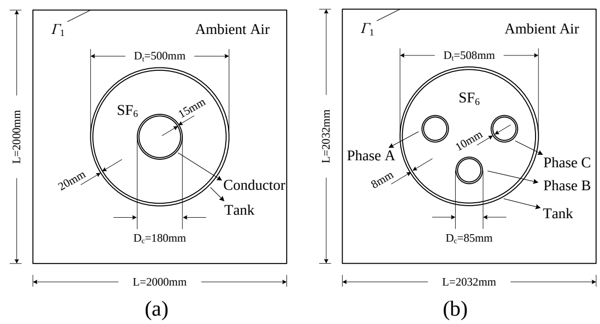


Fig. 1. Solution regions of the gas insulated bus bars (a) Single-phase (b) Three-phase

$$\begin{cases} \Omega : \dfrac{1}{\mu}\nabla^2 A_z = -J_z \\ \Gamma_1 : A_z = 0 \end{cases} \tag{1}$$

where Ω is the solution region, Γ_1 is the Dirichlet boundary condition, μ is the magnetic permeability, A_z is the z component of the magnetic vector potential, J_z is the total current density.

B. Thermal Equations

For multiple species problems, the bulk properties of the gas mixture are calculated with the following equations:

$$\alpha = \sum_{i=1}^{2} \alpha_i Y_i \tag{2}$$

$$\sum_{i=1}^{2} Y_i = 1 \tag{3}$$

where α is the density, thermal conductivity, dynamic viscosity or specific heat of the gas mixture, α_i and Y_i are the material property corresponding to α and mass fraction of the ith species, respectively.

The specific heat of the gas mixture is considered constant. The density, thermal conductivity and dynamic viscosity are, respectively, expressed as [7]

$$\rho = \rho_0 \frac{pT_0}{p_0 T} \tag{4}$$

$$\lambda = \lambda_0 \left(\frac{T}{T_0}\right)^{1.5} \frac{T_0 + S}{T + S} \tag{5}$$

$$\mu = \mu_0 \left(\frac{T}{T_0}\right)^{1.5} \frac{T_0 + S}{T + S} \tag{6}$$

where T is the Kelvin temperature, p is the gas pressure, ρ_0, λ_0 and μ_0 are, respectively, the density, thermal conductivity and dynamic viscosity of the gas mixture at 0℃, S is a constant.

The differential equations governing the steady-state convective heat transfer problem in the present models are [4]

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{7}$$

$$\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+S_x \tag{8}$$

$$\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=\rho g-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+S_y \tag{9}$$

$$\frac{\partial}{\partial x}(\rho uCT)+\frac{\partial}{\partial y}(\rho vCT)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+Q_{\mathrm{v}} \tag{10}$$

where u and v are the respective fluid velocity in x and y direction, S_x and S_y are the sources including distributed resistances and viscous loss terms, C is the specific heat, Q_{v} is the volumetric heat source.

The boundary conditions including the radiation effect considered by energy balance at the surfaces of solids and the constant temperature on the boundary Γ_1 in the solution region, are, respectively, stated as

$$-\lambda\frac{dT}{dx}-\lambda\frac{dT}{dy}=\sigma\varepsilon F_{ij}\left(T_i^4-T_j^4\right) \tag{11}$$

$$T\,|_{\Gamma_1}=T_{\mathrm{a}} \tag{12}$$

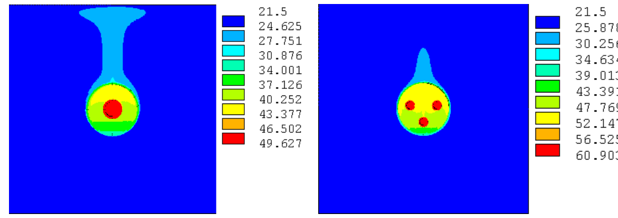
where σ is Stefan-Boltzmann constant, ε is the emissivity of the surface, F_{ij} is the view factor, T_{a} is the ambient temperature.

III. Calculations and Verification

Fig. 2 shows the symmetric temperature distributions of the solution regions corresponding to single- and three-phase bus bars with the load current of 5kA and 2kA, respectively.

Fig. 3 gives the distribution of convective heat transfer coefficient along the tank surface. It is observed that the convective heat transfer coefficient on the outer tank surface has similar distribution for both single- and three-phase bus bars. However, because of the structure difference, the maximum value of the single-phase bus bars locates at the bottom of the tank, while that of the three-phase bus bars is at the horizontal symmetry axis. The minimum values are located at the top of the tank. It can also be observed that the coefficient is not constant at different positions of the tank surface.

The analytical approach is used to compare results with the proposed FEM simulation and test results for the single-phase bus bar referred in [8]. The results are given in Table I. It is observed that the results obtained by the proposed FEM agree with the values calculated with analytical approach, and especially match well with the measured values in single-phase bus bars. As for three-phase bus bars, the discrepancy between the conductor temperatures calculated with the FEM and analytical approach is more than 10% at 2kA, which is mainly attributed to the assumption that the conductors are isothermal and the complexity of convective heat transfer mechanism in three-phase bus bars compared with that of single-phase case in the analytical approach, while the tank temperatures are found to be in good agreement.



(a) (b)

Fig. 2. Temperature distributions of the solution regions (a) Single-phase bus bar (b) Three-phase bus bar

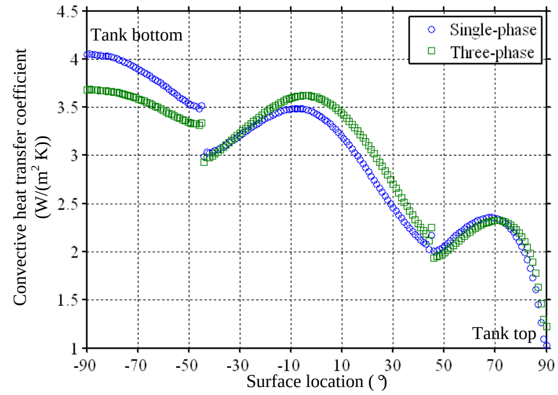


Fig. 3. Convective heat transfer coefficient distribution on the tank surface

TABLE I
Comparison of Calculated and Tested Temperatures (℃)

Method	Single-phase				Three-phase			
	I=5kA		I=7kA		I=1kA		I=2kA	
	T_t	T_c	T_t	T_c	T_t	T_c	T_t	T_c
FEM	35.2	49.6	48.7	74.0	26.3	32.9	38.8	60.9
Analytical	35.0	46.6	48.0	68.4	26.3	30.6	39.6	53.9
Test	36.0	50.0	50.0	72.0	–	–	–	–

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