2005년도 대한전기학회 하계학술대회 논문집 2005. 7. 18 - 20

Modelling and Analysis of Electrodes Erosion Phenomena of SF_6 Arc in a Laval Nozzle

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Abstract - The present work deals with the theoretical study of the effects of copper vapours resulting from the erosion of the electrodes on the properties of a SF6 arc in a Laval nozzle. Computations have been done for a DC arc of 1000A with upstream gas pressure of 3.75MPa. The arc plasma is assumed to be in local thermodynamic equilibrium (LTE). The sheath and non-equilibrium region around the electrodes are not considered in this model. However, its effects on the energy flux into the electrodes are estimated from some experimental and theoretical data. The turbulence effects are calculated using the Prandtl mixing length model. A conservation equation for the copper vapour concentration is solved together with the governing equations for mass, momentum and energy of the gas mixture.
Comparisons were made between the results with and without electrodes erosion. It has been found that the presence of copper vapours cools down the arc temperature due to the combined effects of increased radiation and increased electrical conductivity. The copper vapour distribution is very sensitive to the turbulent parameter. The erosion of upstream electrode (cathode) has larger effects on the arc compared to the downstream electrode (anode) as the copper vapour eroded from the anode cannot diffuse against the high-speed axial flow.

1. Introduction

In SF6 circuit breaker, the high temperature arc causes the erosion of the electrodesresulting in the injection of copper vapours into the arc [1]. The presence of copper vapours modifies the transport properties in particular the electrical conductivity and increases the radiation emission of the arc [2]. This affects the overall energy transfer processes of the arc to the surrounding gas and hence the behaviour of the arc. Previously, the Laval nozzle under consideration has been numerically studied [3] without the presence of downstream electrode and electrode erosion. The main objective of this work is to investigate the effects of copper vapours to the SF6 arc quantitatively. Phoenics, a general purpose computational fluid dynamics (CFD) software isused to implement the arc model.
The experimental setup is described in Section2, and the outline and formulation of the mathematical model are given in Section 3. This is followed by a discussion of the results for a 1000A arc at steady state in Section 4. Finally appropriate conclusions are drawn.

2. Experimental Setup

The schematic diagram of the Laval nozzle is shown in Figure 1. The overall length of the nozzle is 68.75mm, with inlet diameter of 25mm, outlet diameter of 38.4mm and nozzle throat diameter of 12.50mm. The throat position is located at 15.63mm away from the inlet plane. There are two electrodes with the diameter of 4mm. The upstream electrode is fixed, while the downstream electrode is the moving contact.

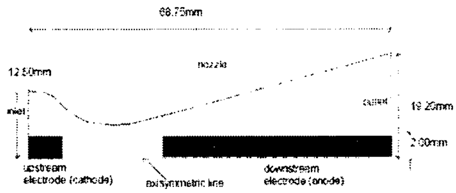


Figure 1 Schematic diagram of the experimental system

3. Formulation and Solution Methodology

It is assumed that the arc is steady state, axisymmetrical and turbulent. Since the pressure is very high, the copper vapour and SF6 are assumed to be completely mixed under Local Thermodynamic Equilibrium (LTE) with the same velocity. The governing equations for mass, momentum and energy of the arc can be written in the following general form as:

$$\nabla \cdot (\rho \vec{V} \phi) - \nabla \cdot (\Gamma_\phi \nabla \phi) = S_\phi \qquad (1)$$

where ρ is the density, $\vec{V}$ the velocity vector, ϕ the dependent variable solved for, Γ_ϕ the diffusion coefficient term and S_ϕ the source terms. All the terms for the governing equations are shown in Table 1, where all notations have their conventional meanings. The subscripts 'l'and 't' denote the laminar and turbulent terms respectively.

Table 1 Terms for governing equations of the arc model

Equation	ϕ	Γ_ϕ	S_ϕ
Continuity	1	0	0
r-momentum	u	$\mu_l + \mu_t$	$-\frac{\partial P}{\partial r} + J_z B_\theta +$viscous terms
z-momentum	ν	$\mu_l + \mu_t$	$-\frac{\partial P}{\partial r} + J_r B_\theta +$viscous terms
Enthalpy	h	$(k_l + k_t)/c_p$	$\sigma E^2 - q +$viscous dissipation
Cu vapour concentration	c_m	$\rho(D_l + D_t)$	0

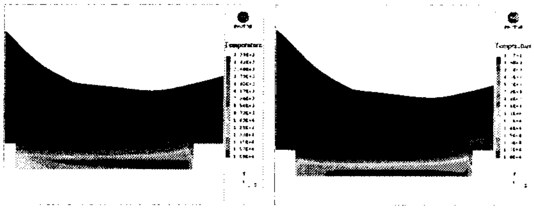
The current density and the electric field are calculated by solving the current continuity equationand the azimuthal magnetic field required to calculate the Lorentz force can be derived from the axial current density distribution according to Ampere's law.

In the present investigation, the sheath and non-LTE region near the electrode is not considered.The change in geometry of electrode due to erosion is neglected. The energy fluxes into the electrodes are estimated, and the rate of production of copper vapours at the electrode is determined according to the approach proposed by [4]. This method enables the introduction of copper vapours as boundary source for mass, momentum and energy at the electrode surface. For the upstream electrode (cathode), the total energy flux considered includes the energy flux carried by ions, thermal conduction, electron emission cooling (Nottingham effects) and cathode material vaporization. The cathode spot is assumed to be a circular conducting region with current density of 2108A/m2. For the downstream electrode (anode),the energy flux carried by the electrons, thermal conduction and anode material vaporization. The semi-empirical radiation model of Zhang [5]is used for the calculation of radiation transfer processes, where the net emission coefficient data obtained from [6].

The thermodynamic and transport properties of the SF6-Cu gas mixture are used according to the same database from [4]. The Prandtl mixing length turbulence model with parameter of 0.10 has been used [3].

4. Results and Discussions

Simulation has been performed for the case of 1000A under steady state condition. The gap between the electrodes is 15mm. The inlet stagnation pressure is 3.75MPa and the static pressure at the nozzle exit is 0.3MPa. There are altogether 140 and 155 cells in the radial and axial direction respectively. First, the simulation for two cases, with and without electrode erosion, has been performed. The temperature distribution with and without the consideration of electrode erosion is shown in Figure 2.



(a) with electrode erosion (b) without electrode erosion

Figure 2. Distribution of temperature with and without electrode erosion with arc current of 1000A, P(up)=3.75MPa, P(down)= 0.3MPa.

It can be observed clearly that with the presence of copper vapour, the arc temperature is reduced considerably. The maximum temperature with the presence of the copper vapour is 16900K, compared with 19000K when electrode erosion is neglected. The radiation loss is increased rapidly with the presence of copper vapour, hence reducing the power input to the arc and this contribute to the lowering of temperature in the core of the arc close to the cathode. The effect of copper vapour on net emission coefficient at pressure of 3.6MPa is shown in Figure 3.

As shown in Figure 4(a), the mass concentration of copper is higher around the cathode region compared with the anode region. This is because the copper vapour eroded at the anode region cannot diffuse against the high-speed axial flow within the arc. The pressure is not sensitive to the presence of copper vapour, and the pressure increase in this case is found to beless than 1%.

The copper vapour concentration distribution is very sensitive to the turbulence diffusion *Dt*. For the case of only laminar diffusion of copper vapour, the concentration distribution is veryhigh in a narrow column throughout the arc core as shown in Figure 4(b). The experimental investigation conducted by Ciobanu et al [7] showed that a strongly emissive copper zone appeared near the electrodes and a weekly emissive zone between the electrodes. This confirms the turbulent diffusion is of such importance to the transport and distribution of copper vapour concentration within the arc.

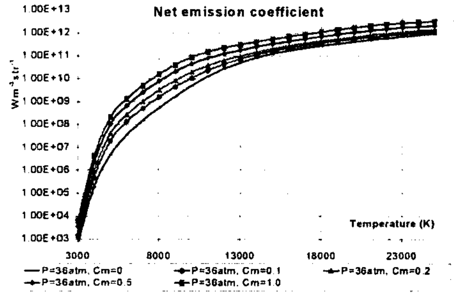
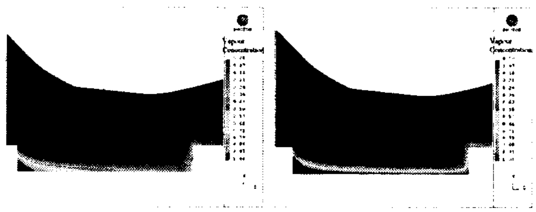


Figure 3. The Net emission coefficients of SF6-Cu mixture at 3.6MPa and arc radius of 1mm [6]



(a) with turbulent diffusion term (b) without turbulent diffusion term

Figure 4. Distribution of copper vapour concentration with arc current of 1000A, P(up)=3.75MPa, P(down)= 0.3MPa with and without turbulent diffusion term.

The axial distribution of arc temperature, axial velocity, arc voltage and copper concentration is displayed on the same diagram in Fig.5 in order to compare the effects of electrode erosion. At the region very close to cathode surface, the arc burns in pure copper vapour and the copper concentration decreases rapidly until around 1mm away from anode surface where it increases rapidly to 60% copper mass concentration due to the vaporisation of anode surface. With the presence of copper vapour, the axial temperature is around 3000K lower compared with the case without electrode erosion, while the maximum axial velocity reduces from 1970m/s to 1700m/s. The arc voltages are not sensitive with the copper vapours which are found to be around -420V for both cases.

Figure 6 shows the radial profile of ohmic heating and radiation loss at 4mm away from the cathode. The copper vapour concentration, electrical conductivity and arc temperature are also plotted in the same diagram. With copper vapour, the ohmic heating arc core reduces to around 11013Wm-3compared with 1.21013Wm-3without electrode erosion. However, the radiation loss at the arc core has similar value of 11013Wm-3 for both cases. As the results, a higher arc temperature of 19000K is established without electrode erosion compared with 16000K with the presence of copper vapour. The arc radius is biggerin the presence of copper vapour because the electrical conductivity increases rapidly in the range of 4000K to 10000K which increases the ohmic heating at the arc edge.

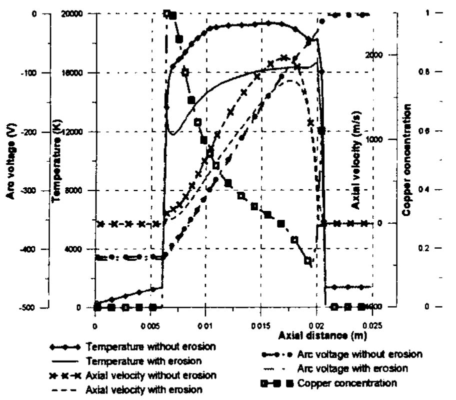


Figure 5. The distribution of arc temperature, axial velocity and arc voltage with and without copper erosion on the axis. The copper concentrationdistribution for the case with electrode erosion is plotted on the same curve.

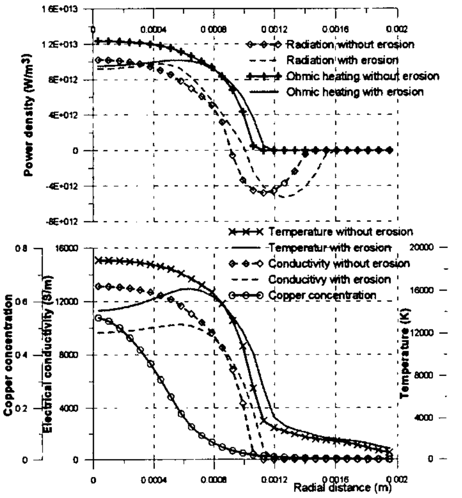


Figure 6. The radial profiles at 4mm away from the cathode surface for ohmic heating, radiation loss, electrical conductivity and arc temperature for the case with and without electrode erosion. The copper vapour concentration profile is plotted for the case with erosion.

The effects of electrode gap distance have also been investigated. Figure 7 shows the arc temperature, axial velocity and pressure distributions along the axis for electrode gap distance of 10mm, 15mm and 20mm. The temperature and axial velocity increase when the electrode gap is increased. The higher pressure gradient for larger electrode gap forces the velocity to increase. The total arc voltages for the three cases have been found to be -283V, -418V and -535V, while the corresponding maximum velocities attained are 958m/s, 1700m/s and 2874m/s respectively. The effects of electrode gap on total arc voltage, maximum temperature and maximum velocity are shown in Figure 8.

5. Conclusion

The influence of copper vapour due to electrode erosion in a Laval nozzle has been numerically investigated. Computational results show that the arc temperature typically drops from 19000K to 16000K with the presence of copper vapour. The arc voltage and pressure are not sensitive to the copper vapour. The arc temperature, voltage, velocity and pressure have been found to be very sensitive to the electrode gap distance. Future work will be done to include

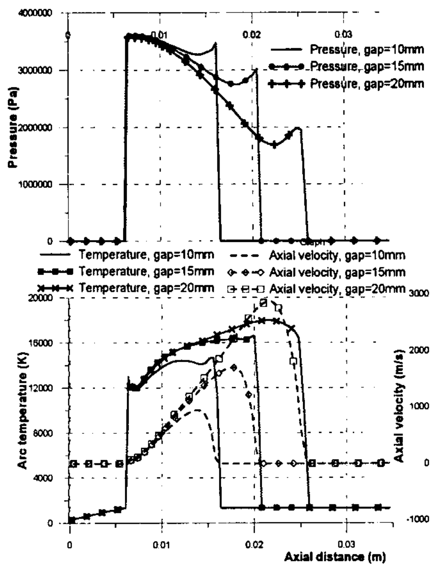


Figure 7. The arc temperature, axial velocity and pressure along the axis for different electrode gap of 10mm, 15mm and 20mm.

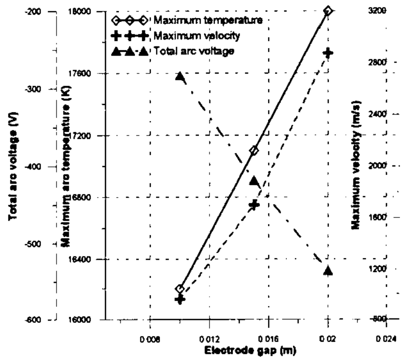


Figure 8. The effects of electrode gap on maximum temperature, velocity and total arc voltage.

the numerical investigation for different arc currents, followed by the transient simulation of the arc at current zero.

[참 고 문 헌]

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