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CAE Analysis of SF_6 Arc Plasma for a Gas Circuit Breaker Design

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가스차단기 최적설계를 위한 SF_6 아크 플라즈마 CAE 해석

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Keywords : *Gas Circuit Breaker(가스차단기), Arc Plasma(아크 플라즈마), Approximation Radiation Model(간이복사모델),Ohmic Heating(주울열), Lorentz Force(로렌츠 힘)*

Abstract

The design of industrial arc plasma systems is still largely based on trial and error although the situation is rapidly improving because of the available computational power at a cost which is still fast coming down. The desire to predict the behavior of arc plasma system, thus reducing the development cost, has been the motivation of arc research. To interrupt fault current, the most enormous duty of a circuit breaker, is achieved by separating two contacts in a interruption medium, SF_6 gas or air etc., and arc plasma is inevitably established between the contacts. The arc must be controlled and interrupted at an appropriate current zero. In order to analyze arc behavior in SF_6 gas circuit breakers, a numerical calculation method combined with flow field and electromagnetic field has been developed. The method has been applied to model arc generated in the Aachen nozzle and compared the results with the experimental results. Next, we have simulated the unsteady flow characteristics to be induced by arcing of AC cycle, and confirmed that the method can predict arc behavior in account of thermal transport to SF_6 gas around the arc, such as increase of arc voltage near current zero and dependency of arc radius on arc current to maintain constant arc current density.

1. Introduction

This study is concerned with the simulation of SF_6 arc interrupter and the arc in such an interrupter. The arc was discovered by Davy and Rutter in 1808, and has a number of applications such as welding and materials processing [1]. We shall be concerned with its use in current interruption devices, or simply, interrupters.

The interrupter forms one part of a device known as a circuit breaker. The interrupter always makes use of a pair of moving metallic contacts separated by a mechanical mechanism, which is the other main component of a circuit breaker. The most onerous duty of a circuit breaker is to interrupt fault current in a circuit, thereby protecting other components from damage. This is achieved by separating the two contacts in a gas or a liquid, and an arc is inevitably established between the contacts. The arc must be controlled during the high current period of the AC cycle and interrupted at an appropriate current zero.

Interrupters have passed through a number of phases in their design over the years, and a number of materials have been used as arc quenching medium. Oil has been used as arc quenching medium for a number of years. The oil molecules dissociate in the high temperature of the arc producing a bubble of hydrogen gas. This bubble is usually confined by some types of arc control devices and allowed expand past the arc, thereby cooling the arc and causing the arc to be extinguished. Air has also been used as the interrupting medium. Airbreak interrupters employing magnetic lengthening of the arc in arc chutes were developed by Slepian at Westinghouse in 1929. For higher voltage levels air-blast circuit breakers were developed in which the arc is cooled by a high-speed blast of air. This type of breaker was used at the highest voltage levels until the use of SF_6 gas as the interrupting medium became widespread. Although oil and air technologies were successful, they have disadvantages which led to continued development in interrupter design. Oil is highly flammable and accidents with oil filled interrupters can lead to oil fires. Also maintenance of this type of interrupter is unpleasant. Air blast interrupters are very complex with a large number of components. They are subsequently very expensive and the large number of components implies a low level of reliability. Also they are very noisy. In the 1950's the excellent interrupter, which produces the high-pressure gas required using the operation of a simple piston arrangement, has been the most common type until now, but the auto-expansion interrupter using part of the arc energy itself

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to aid in the interrupter process is developing.

In this paper we describe the arcing process during a high-current period in the auto-expansion interrupter. In order to analyze arc behavior in SF_6 gas circuit breakers, a numerical calculation method combined with flow field and electromagnetic field has been developed. The method has been applied to model arc generated in the Aachen nozzle and compared the results with the experimental results [2]. Next, we have simulated the unsteady flow characteristics to be induced by arcing of AC cycle in SF_6 gas circuit breaker, and confirmed that the method can predict arc behavior in account of thermal transport to SF_6 gas around the arc, such as increase of arc voltage near current zero and dependency of arc radius on arc current to maintain constant arc current density.

2. GOVERNING EQUATIONS

The governing equations of a turbulent arc and its surrounding flow are the time-averaged Navier-Stokes equations written in conservative form

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla\cdot\left(\rho\phi\vec{V}\right)-\nabla\cdot\left(\Gamma_\phi\nabla\phi\right)=S_\phi \qquad (1)$$

where ϕ is the dependent variables, ρ the gas density, Γ_ϕ the diffusion coefficient and S_ϕ the source term. For the calculation described in this paper four such equations are solved. In these equations, ϕ represents axial velocity, radial velocity, enthalpy and electric potential. The pressure field is also solved by making use of the continuity equation.

2.1 Flow field calculation

The meaning of ϕ, Γ_ϕ and S_ϕ for the momentum equations and the enthalpy equation are shown in table 1, where μ is the laminar viscosity, μ_t the turbulent viscosity, k the thermal conductivity, k_t the turbulence enhanced thermal conductivity, σ the electrical conductivity, j the current density, E the electric field and q the radiation emission.

Table 1 Meaning of ϕ, Γ_ϕ and S_ϕ for the momentum and the enthalpy equations.

Equations	ϕ	Γ_ϕ	S_ϕ
Axial mom.	w	$\mu+\mu_t$	$S_w=-\frac{\partial p}{\partial z}+\left(j\times B\right)_z+viscous\ \ terms$
Radial mom.	v	$\mu+\mu_t$	$S_v=-\frac{\partial p}{\partial r}+\left(j\times B\right)_r-\frac{\partial(\mu+\mu_t)v}{r^2}+other\ \ viscous\ \ terms$
Enthalpy	h	$k+k_t/c_p$	$S_h=\frac{dp}{dt}+\sigma E^2+q+viscous\ \ dissipation\ \ terms$

2.2 Electromagnetic field calculation

The electric potential is found from the equation for conservation of current,

$$\nabla\cdot\left(\sigma\nabla\phi\right)=0 \qquad (2)$$

The boundary conditions for this variable are as follows. Axisymmetric conditions are set on the axis at r=0 and we set $\partial\phi/\partial n=0$ at all other boundaries apart from the contacts. On one of the contacts we set $\phi=0$ and solve equation (2) with the potential on the other at an arbitrary fixed value, say 5V. From the resulting potential field we calculate the electric field and the total current which would result from a 5V potential difference. The electrical conductivity in the SF_6 gas is found from tabulated values. For the non-conducting part of the gas, outside of the arc, the electrical conductivity is set to a small value. This allows the calculation of the potential throughout the nozzle which giving the correct condition at the arc edge (no current normal to the arc edge). The electrical conductivity in the contacts is set to a high value. This allows the calculation of the electric potential in the contacts and removes the need to set a cathode spot.

The magnetic field in this device has only an azimuthal component caused by the arc itself. This azimuthal field at a radius, *r* can be calculated by Ampere's circuital law,

$$B=\frac{\mu_0\int_0^r J_z 2\pi\zeta d\zeta}{2\pi r} \qquad (3)$$

where J_z is the axial component of current density and μ_0 the permeability.

2.3 Radiation model

The approximate radiation model of Zhang et al. [3] was first used in modeling of a nitrogen nozzle arc. Subsequently it has been successfully applied to SF_6 nozzle arcs and to the modeling of an SF_6 autoexpansion circuit breaker. The model is one-dimensional and assumes an axisymmetric arc in which radiation transport occurs only in the radial direction (i.e. axial energy transport in one direction is balanced by equal transport in the opposite direction). Such a model is expected to perform well if axial variation in temperature is slow compared with radial variation.

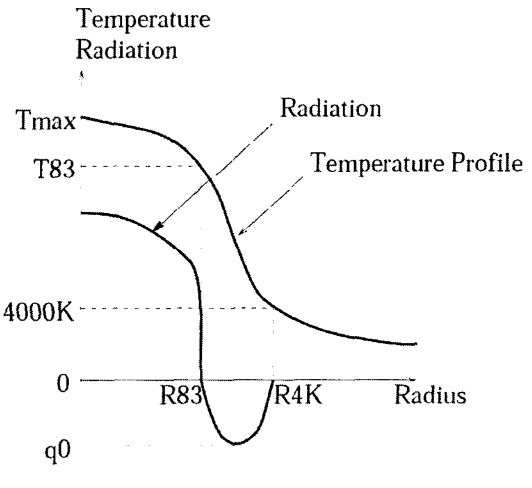

Fig. 1 Schematic diagram of approximate radiation model.

A schematic diagram describing the model is shown in figure 1. Two radial regions are considered. In the central part of the arc from the axis to the point where the temperature is 83% of the axis temperature there is emission of radiation. At the edge of the arc from the point where the temperature is 83% of the axis temperature to the point where the temperature 4,000K, there is reabsorption of the radiation. The profile of the reabsorption is assumed to be a parabola and the fraction of the radiation reabsorbed is fixed.

In summary the approximate radiation model is a semi-empirical one-dimensional model of which attempts to simplify the physics for the radiation transfer in arcs at minimum computational cost. The model appears very successful in a number of applications, but has a couple of free parameters that must be fixed.

2.4 Turbulence model

It has been observed that SF_6 arcs are often turbulent and Prandtl mixing length model was used successfully for a SF_6 nozzle arc by Fang et al. [4]. Using this model, the turbulent viscosity is given by

$$\mu_t = \rho(c\delta)^2 \left|\frac{\partial w}{\partial r} + \frac{\partial v}{\partial z}\right| \qquad (4)$$

where δ is the arc thermal radius given by

$$\delta = \sqrt{\int_0^{R_{2K}} (1-\rho/\rho_{2K})2r\,dr} \qquad (5)$$

and c is a turbulent parameter which is adjusted according to experimental results. The integration in equation (5) is c arried out from r=0 to the first point at which the temperature is 2,000K.

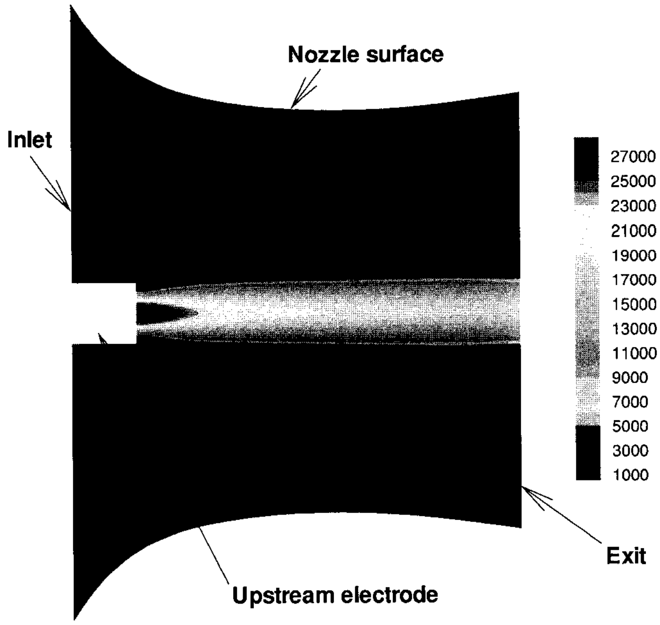

Fig. 2 Temperature distribution for the Aachen nozzle at 1800A.

3. RESULTS AND DISCUSSION

3.1 Results for the Aachen nozzle

Calculations of SF_6 arc plasma for the Aachen nozzle have been carried out at 600A and 1800A and the resulting temperature distribution for a current 1800A is shown 1800A is shown in figure 2. The upstream stagnation pressure is 9 bar and the stagnation temperature is set to 300K. The exit static pressure is 2.5 bar. The length nozzle is 55mm and the throat diameter is 36.7mm. The distance between the inlet and the nozzle throat is 33mm. The diameter of the upstream electrode is 10.86mm and its length is 7.86mm.

In figure 3 the radial temperature distribution at the throat of the nozzle calculated is shown together with the experimental results for a currents of 600A and 1800A. It can be seen that the calculated results are a good match to the experimental results. Therefore, the model used in this arc plasma study may be valid to analyze the unsteady flow characteristics to be induced by arcing of AC cycle in SF_6 gas circuit breaker.

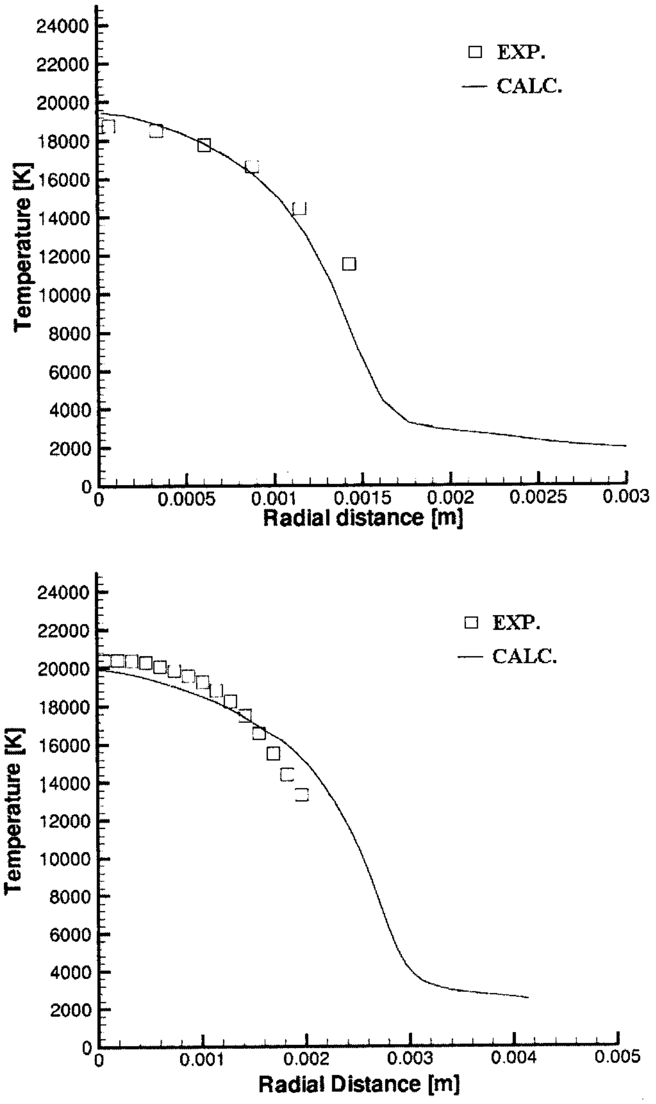

Fig. 3 Temperature distributions at the nozzle throat of the Aachen nozzle for currents of 600A(up) and 1800A(down).

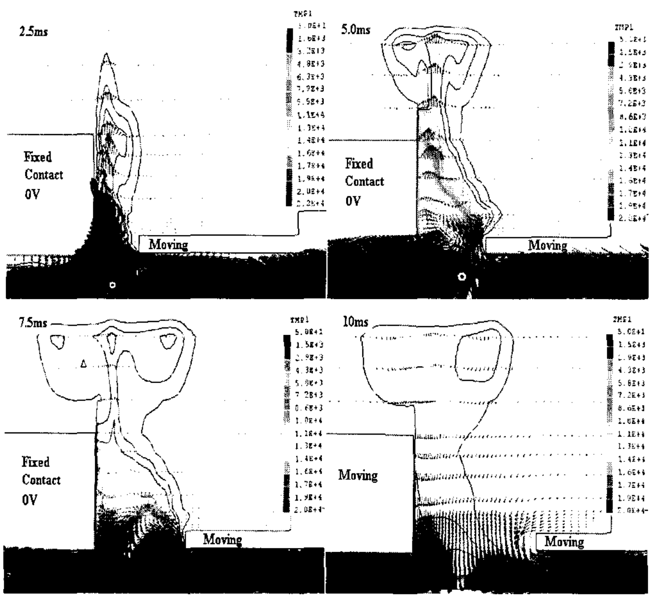

Fig. 4 Temperature distribution and velocity vectors under current variations such as 5kA(2.5ms), 10kA(5ms), 5kA(7.5ms) and 0.2kA(10ms), respectively.

3.2 Results for the SF_6 gas circuit breaker

A calculation has been carried out for a single loop sinusoidal current with a peak value of 10kA. The frequency is taken as 50Hz giving a duration of 10ms. The filling pressure of the device is taken to be 2bar (abs) and the contact speed to be 3m/s. In this simulation the cathod is taken to be at the fixed contact.

The temperature and the pressure inside the chamber are beginning to rise just after finishing the period of initialization. The temperature distributions and velocities are shown in figure 4 under current variations such as 5kA, 10kA, 5kA and 0.2kA, respectively. In the period of 2.5ms (5kA) the arc energy flows into the chamber and causes the pressure in the chamber to rise. In 5ms (10kA), the peak time of current, the hot gas heated by the arc extends to the top of the fixed contact. After that, the hot gas is developed to the axial direction and reversed toward the outlet by the pressure increased in chamber. Therefore this interrupter has an ability to blow the arc near current zero.

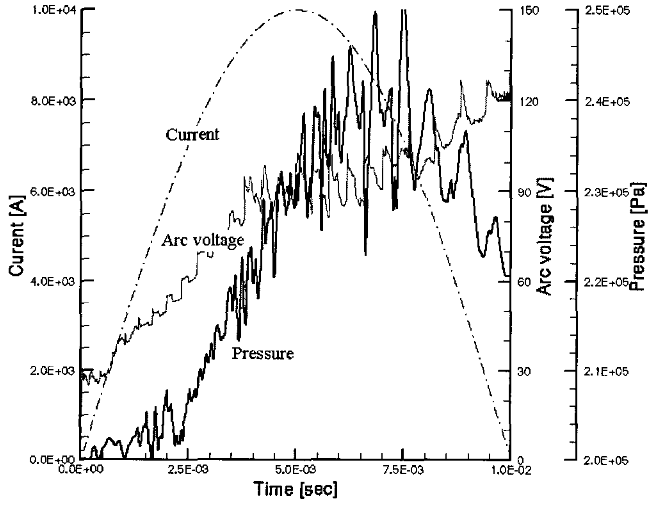

Fig. 5 The arc voltage and pressure rise in the chamber as a function of time.

The arc voltage and pressure rise occurred during the arcing period are shown in figure 5. The pressure is monitored in the chamber close to the outer wall and at an axial position level with the initial position of the moving contact. Through the high current period the arc voltage is about 40~120V. The maximum pressure rise is 0.4bar. The pressure rise may be affected by the amount of radiation absorbed in the cold gas. There is a delay between the peak of the current and the peak of the pressure rise. This is consistent with the published results of many researchers [6]. Energy is added throughout the arcing period and the pressure only begin to drop as the current reaches a relatively low value so that the hollow contacts are no longer blocked by the arc.

4. CONCLUSIONS

The results are summarized as follows:

1) Calculation results of SF_6 arc plasma for the Aachen nozzle carried out at 600A and 1800A are a good match to the experimental results. Therefore, the model used in this arc plasma study may be valid to analyze the unsteady flow characteristics to be induced by arcing of AC cycle in SF_6 gas circuit breaker.

2) The energy produced by arc causes the pressure in the chamber of SF_6 gas circuit breaker to rise during high current period and the interrupter has an ability to blow the arc near current zero.

3) Through high current period the arc voltage is about 40~120V and the maximum pressure rise is 0.4bar. There is a delay between the peak of the current and the peak of the pressure rise.

4) However to apply this calculation method with the real design of a gas circuit breaker, there are many difficulties to be resolved such as the calculation of transient recovery voltage and post-arc current just after current zero. It is required to study more for the experiments that may support the physics in the device.

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