Dynamic Arc Modelling Based on MHD Equations for SF₆ Circuit Breaker Using FEM

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ABSTRACT
In this paper, a dynamic arc model based on MHD (Magneto Hydro Dynamic) equations for a high voltage (HV) SF₆ interrupter has been investigated and analyzed. Moreover, for simulating the insulating performance and interrupting characteristics of the SF₆ interrupter, dynamic variation of the arc, and energy-balance equations. The distributions of temperature field, pressure field, and mass fraction in the arc chamber are calculated. Keywords: Arc, dynamic, electromagnetic, mass, simulation.

1. INTRODUCTION
SF₆ gas is widely used as an insulation and arc-quenching medium in electric apparatus because of its excellent insulating performance in uniform electric field and extended in HV, extra HV, and ultra HV circuit breakers (CBs). The kernel problem to be investigated is dielectric recovery characteristic and interrupting performance, which mainly depend on the combined effects of the electric field and gas flow state in the arc quenching chamber during the interrupting process and the arc energy dynamic simulation. The interrupting process in a CB involves different phases, and considerable knowledge has been covered in the understanding of the physical processes, which bring great difficulties for investigating the opening property [1]. Moreover, flow field computation within the SF₆ interrupting medium is extremely difficult due to the complex flow path with stride sonic flow, active, viscous, compressible, variable boundary, and some intricate physical phenomena, such as shock waves and vortices during interrupting. Recently, inherent weakness has been reported lying in the simplifications of computing structure and arc modeling. The aim of this paper is to solve the numerical problem with complex flow path and space-time processing synchronously, a coupled field mathematical model of electric field and flow field has been established.

2. Model description
The simple model presented in this paper assumes 2-D axisymmetric lamp geometry. The discharge is assumed to be in local thermodynamic equilibrium (LTE). The difference reported between the LTE and non-LTE electrical conductivities were in the cathode-sheath [2], where the electrical conductivity is generally very low. Therefore, a non-LTE situation in such lamps would be very local and its effect on total lamp characteristics may not be significant. In this paper the model that presented in [3], has been used. The following are the set of equations that are solved in the steady-state system:

1. Mass continuity
\[ \frac{\partial}{\partial z}(pu) + \frac{1}{r} \frac{\partial}{\partial r}(rpu) = 0 \]  

2. Momentum conservation
\[ \frac{1}{r} \frac{\partial}{\partial z}(rpuu) + \frac{1}{r} \frac{\partial}{\partial r}(rpuv) = -\frac{\partial p}{\partial z} + F_z - \rho g + \frac{\partial}{\partial z} \left( 2\mu \frac{\partial u}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right) \]  

3. Energy conservation
\[ \frac{\partial}{\partial z}(upH) + \frac{1}{r} \frac{\partial}{\partial r} (rpuH) = \frac{\partial}{\partial z} \left( k \frac{\partial H}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( k \frac{\partial H}{\partial r} \right) + \frac{5k}{2r} \left( \frac{\partial H}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{1}{c_p} \frac{\partial H}{\partial r} + \frac{1}{c_p} \frac{\partial H}{\partial r} \right) + \sigma E^2 - R - \text{div} \left[ \kappa_H \overrightarrow{v} \right] \]  

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4) Chemical species conservation for Ar
\[
\frac{\partial}{\partial z}(u p_{\text{Ar}}) + \frac{\partial}{\partial r}(u p_{\text{Ar}}) = - \frac{\partial}{\partial z}\left( \rho D_{\text{Ar},m} \frac{\partial m_{\text{Ar}}}{\partial z} \right) - \frac{\partial}{\partial r}\left( \rho D_{\text{Ar},m} \frac{\partial m_{\text{Ar}}}{\partial r} \right)
\]  
(5)

The solution of argon-mass conservation helps to calculate the mercury-mass concentration automatically since the total mass concentration of Ar and Hg is 1.

5) Curl of Ampere’s law for magnetic field
\[
\frac{\partial}{\partial z} \left( \frac{\partial B_z}{\partial r} \right) + \frac{\partial}{\partial r} \left( r \frac{\partial B_r}{\partial r} \right) = 0
\]  
(6)

6) Laplace’s equation for electrostatic potential
\[
\frac{\partial}{\partial z} (\sigma \frac{\partial^2 V}{\partial z^2}) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \sigma \frac{\partial V}{\partial r} \right) = 0
\]  
(7)

Where, \( \sigma \) and \( k \) are the electrical and thermal conductivities; \( \rho, \mu, C_p, \) and \( H \) are the mass density, viscosity, heat capacity and enthalpy, respectively; \( h_{Hg} \) and \( h_{Ar} \) are the enthalpies of Hg and Ar, respectively; \( J_{Hg} \) and \( J_{Ar} \) are the diffusion fluxes of Hg and Ar respectively; \( m_{Ar} \) and \( D_{Ar,m} \) are the local mass concentration and diffusion coefficient of Ar, respectively; \( u \) and \( v \) are the axial and radial velocities, respectively; \( B_0 \) is the azimuthal component of the magnetic field intensity; \( F_z \) and \( F_r \) are the axial and radial Lorentz forces, respectively; \( V \) is the electrostatic potential; \( J_z \) and \( J_r \) are the axial and radial current densities, respectively; and \( g, e, E \) and \( \mu_e \) are the gravitational acceleration, electronic charge, electric field intensity and permeability of free space, respectively. \( R \) on the right-hand side of the energy equation represents the volumetric radiated loss and it is included into the calculation scheme using either the net emission coefficient or mean absorption coefficient
\[
R = 4\pi e_B = \alpha (4\pi B - G)
\]  
(8)

Where \( e, \alpha, B, \) and \( G \) are the net emission coefficient, absorption coefficient, Plank’s function, and incident radiation (or integrated incident radiation over all solid angles), respectively. The P-1 radiation model is employed when the mean absorption coefficient is used to calculate the mean incident radiation and, thus, the radiation loss. Note that the mean absorption coefficient and the mean incident radiation are the averaged absorption coefficient and incident radiation over a band. A Helmoltz- type equation of the following form is solved for the mean incident radiation \( G_i \) of the band \( i \) when the P-1 model is used:
\[
\frac{\partial}{\partial z} \left( \frac{1}{\alpha_i} \frac{\partial G_i}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{1}{\alpha_i} \frac{\partial G_i}{\partial r} \right) = -\alpha_i (4\pi B_i - G_i)
\]  
(9)

3. Case study

The following assumptions were made to reduce the complexity of the simulation because it has been interested in the motion of the arc column rather than the chemical processes of the arc.
1) The plasma studied was assumed to satisfy the conditions for local thermodynamic equilibrium, and the flow was laminar [4]-[6].
2) The arc–electrode interaction was not modeled.
3) The plasma was considered to be high-temperature air with the thermodynamic and transport properties obtained from the literature [7-11]. The physical properties, including thermal conductivity, viscosity, density, specific heat, and electrical conductivity, were functions of the plasma temperature and pressure.
4) The plasma was assumed to be electrically neutral. This condition was nearly exactly fulfilled with the arc column. However, this so-called sheath region, i.e., space charge region close to the electrode with violated quasineutrality, was ignored since the behavior of the plasma in the arc column was the focus of this paper, and its interaction with the surroundings was of primary importance in switching applications.
5) The arc-plasma flow can be regarded as a moving conductor in a magnetic field, and then, it was assumed that the induced current given by the transient terms in Maxwell’s equations was small compared to the injected current from the circuit. It was therefore neglected.
6) No ferromagnetic materials in the domain were presented, thus, justifying the use of a constant permeability for the gaseous medium in order to simplify the calculation of the magnetic field.

The arc plasma can then be modeled by the Navier–Stokes equations to describe the mass, momentum, and energy conservation processes, and Maxwell’s equations to describe the electromagnetic processes. In addition, in accordance with the physical process of the arc column, to reflect the ohmic heating and radiative cooling, together with the Lorentz force on the plasma due to self-induced and external magnetic fields, it is necessary for the simulation of the arc to include source terms in the energy and momentum equations.

Figure 1 shows the calculation model. The calculation plane ABCD was parallel to the electrode, or perpendicular to the arc column. The region geometry was 80 \times 14 \text{ mm}, which was just the same as the experimental model. The grid size was 0.2 \times 0.2 \text{ mm}. The boundary conditions are as follows.
1) To boundaries AB, CD, and AD, the adiabatic conditions were assumed for thermal conditions, and no-slip conditions were specified for velocity.

2) To full open venting BC, the static pressure was equal to zero, and the temperature was set to environment temperature of 300 K.

It was assumed that arc current flowed out from the paperplane, and with the action of external magnetic field of y-direction, which was consistent with the experimental conditions and set to 5 mT, together with the gas flow, the arc may move toward the venting.

Due to the peak values of current and the ignition current of the aforementioned experimental results were all almost equal to 200 and 100 A, respectively, the simulation current could be expressed by $i = 200 \sin(100\pi t + \pi/6)$.

![Figure 1: Selected model of arc chamber](image)

5. Simulation and results

Figure 2 shows the temperature distribution of the arc at 1 ms. The arc has been formed in the central part of chamber. It has several layers, very hot, hot, cool and etc. Conductivity of these layers is a function of their temperature. Figure 3 shows temperature distribution of the arc at 10 ms. It can be seen that during less than 10 ms, the arc temperature increases very fast. Significant part of current flows from central part of arc. Following the development of the study, temperature distribution of the arc at 10 ms with the presence of electromagnetic force has been simulated (Figure 4).
Using Navier-Stokes equations, the mobility of arc due to Lorentz force can be simulated. This mechanism is used for better cooling and interrupting of arc in its chamber. This method is widely used in gas circuit breakers.
6. Conclusion

This paper presents results for MHD simulation that can be used for studying a SF6 circuit breaker. The P-1 radiation method applied in this work is used to predict the radiation output from the arc. Although this method tends to over predict radiation flux density in optically thin walls, it is computationally efficient and gives reasonably good quantitative information about the temperature profile and radiative flux. Parametric studies using such a model should help reduce the development times for new CB designs. In the example presented in this paper, it has been provided results for a CB with a medium consisting of SF6 gas. The maximum temperature within CB operating at a pressure of 1.1 atm and a current of 200 A is 12000 K. From the study of this paper, the following conclusions could be drawn.

1) The arc ignition position has an important effect on the arc-motion process. The less volume behind the arc is, the faster the arc-motion velocity will be.
2) If the back venting is open fully, i.e., the volume behind the arc is large enough; the arc almost does not move forward.
3) The arc-motion velocity could be improved significantly with the action of the gassing material, which also benefits to improve the interruption performance to some extent.

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