The Effects of SF$_6$-Cu Mixture on the Arc Characteristics in a Medium Voltage Puffer Gas Circuit Breaker due to Variation of Thermodynamic Properties and Transport Coefficients

Vahid ABBASI$^1$, Ahmad GHOLAMI$^1$, Kaveh NIAYESH$^2$

$^1$Electrical Engineering Department, Iran University of Science and Technology, Narmak, Tehran, Iran
$^2$School of Electrical and Computer Engineering, College of Engineering, University of Tehran, IR-14395 Tehran, Iran

Abstract In a gas circuit breaker, metal vapor resulting from electrode erosion is injected into the arc plasma. The arc then burns in a mixture of SF$_6$ and electrode vapor, which has properties significantly different from those of pure SF$_6$. Thermodynamic properties and transport coefficients of thermal plasmas formed in SF$_6$-copper vapor mixtures change as a function of temperature and pressure. The property that is mostly affected by the presence of copper is electrical conductivity, which is important in magnetohydrodynamic (MHD) analysis. In this study, the transport coefficients of SF$_6$ in the presence of 10 percent copper are considered as the basis of MHD simulation. Comparisons are made between the results during arc formation for pure SF$_6$ and SF$_6$-Cu mixture in a medium voltage (MV) circuit breaker. According to the transport coefficients influenced by the SF$_6$-Cu mixture, the distribution of the electric potential, temperature, electromagnetic force density and current density of the arc column are presented and discussed. Also, the arc stability and pinch effect near current zero with 3-D simulation are investigated, which is advantageous to improving the efficiency of arc plasma simulation.

Keywords: magnetohydrodynamic (MHD), electromagnetic force, SF$_6$-Cu mixture, transport coefficients, pure SF$_6$

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1 Introduction

Due to its excellent dielectric strength and interruption performance, SF$_6$ is widely used in gas circuit breakers (GCB) and gas insulated switchgear (GIS), especially for the high voltage class above 110 kV. It is very necessary to investigate the SF$_6$ arc interruption process in high voltage circuit breakers, in order to facilitate the design of products with higher performance and lower developmental cost [1∼3]. During the past 20 years, many researchers relevant to SF$_6$ high voltage circuit breakers have developed arc models based on magnetohydrodynamics (MHD) [4∼5]. In addition, arcs involve ablation of walls and electrodes by radiation, which causes impurities. Numerical investigations must include these impurities in the physical modeling of arcs since they can modify arc characteristics. The presence of impurities, especially copper, tends to change transport coefficients such as electrical conductivity, thermal conductivity, viscosity and density, all of which affect the interruption capability [6∼9].

The arc transport nonlinear coefficients are dependent on the arc temperature and pressure of the flow field. Electrical conductivity of the arc plasma defines the distribution of the electric potential and current density. Also, the arc current induces the magnetic field and Lorentz force. Joule heating serves as a heat source and the Lorentz force serves as a momentum source. Therefore, the electric and magnetic fields play an important role in the arc behavior and deformation. These relations confirm the importance of gas combination during the arc in a circuit breaker.

In this paper, a numerical study of Cu contaminated SF$_6$ is presented. The transport coefficients for SF$_6$ and the SF$_6$-Cu mixture are extracted from previous experimental and theoretical research [6∼9]. The current research mainly contributes to the calculation of the temperature, electric potential, electromagnetic force density and its influence on arc stability during operation in the presence of copper. 3D simulation results in the paper provide a suitable view of the physical phenomena that make the nature of the arc more visible.

2 Numerical modeling

2.1 MHD equations

The coupled interactions among the arc current, magnetic field, and plasma flow are described in the framework of MHD equations in conjunction with the
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K-ε turbulence model [10-16], where K and ε are the turbulent kinetic energy and its dissipation rate, respectively. The K-ε model has been widely adopted for arc plasma modeling [11,12,15-17] and the recent numerical studies on turbulence effects in arc simulation have shown that the K-ε model predicts the calculated net plasma powers close to the measured ones more accurately than the laminar model [15]. The 3D distribution of arc current j is obtained from the current continuity equation \( \nabla \cdot j = 0 \), along with the generalized Ohm’s law:

\[
j = \sigma (-\nabla \varphi + \mathbf{v} \times \mathbf{B}),
\]

where \( \sigma, \mathbf{v} \) and \( \varphi \) are the electric conductivity, the plasma velocity and electric potential, respectively. The self-induced magnetic field is found using the magnetic vector potential \( \mathbf{A} \) from \( \mathbf{B}_{arc} = \nabla \times \mathbf{A} \), where the magnetic vector potential is determined from Ampere’s law as follows:

\[
\nabla^2 \mathbf{A} = -\mu_0 \mathbf{j},
\]

with \( \mu_0 = 4\pi \times 10^{-7} \text{Tm}A^{-1} \).

The time dependent equations for the transports of mass, momentum, and energy of plasma flow are described by the conservation laws in the following:

a. Conservation of mass

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0.
\]

b. Conservation of momentum

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = \mathbf{j} \times \mathbf{B} - \nabla p + \nabla \cdot \mathbf{\tau}.
\]

c. Conservation of energy

\[
\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \mathbf{v}) = \mathbf{j} \cdot \mathbf{E} - \dot{\mathbf{R}} + \nabla \cdot (k \nabla T),
\]

where \( \rho, p, \tau, h, \dot{\mathbf{R}} \) and \( T \) are the plasma density, pressure, stress tensor, enthalpy, radiation loss and temperature, respectively.

Energy transport by radiation in an arc plasma system is an extremely complex and important phenomenon [18]. The radiation flux at a particular position is not only a function of the local gas properties, but also dependent on the temperature and pressure. LIEBERMANN and LOWKE [19] calculated the net emission coefficient of SF₆ at the center of an isothermal and cylindrical arc column under uniform pressure [20]. Most researchers use the model in their investigations [18] and in some cases it has been modified [21]. The radiation loss is taken into account by using the net emission coefficient.

In order to take into account the turbulent effects produced by arc gas, a standard K-ε model is employed, in which the turbulent viscosity \( \mu_t \) and the turbulent thermal conductivity \( k_t \) are defined as:

\[
\mu_t = \rho C_{\mu} K^2 / \varepsilon \quad \text{and} \quad k_t = \mu_t c_p / P_{tr},
\]

where \( C_{\mu}, P_{tr} \), and \( c_p \) are the constants in the turbulence model, turbulent Prandtl number, and specific heat, respectively [11,12]. The two turbulence variables \( K \) and \( \varepsilon \) are obtained by solving the following two equations as given in [11]:

a. Turbulent kinetic energy

\[
\frac{\partial (\rho K)}{\partial t} + \nabla \cdot (\rho \mathbf{v} K) = G - \rho e + \nabla \cdot [(\mu_i + \mu_t) \nabla K].
\]

b. Dissipation rate of turbulent kinetic energy

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{v}) = \frac{\varepsilon}{K} (C_1 G - C_2 \rho e) + \nabla \cdot [(\mu_i + \mu_t) \nabla \varepsilon].
\]

where \( \mu_1, \mu_t, \varepsilon \) are the constants suggested by Launder and Spalding. In addition, \( G \) is the turbulent generation term expressed as:

\[
G = \mu_i \left[ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right] \frac{\partial v_i}{\partial x_j}
\]

2.2 Transport coefficients

At high temperatures, Cu dissociates and SF₆-Cu mixtures are produced as a result of dissociation. The mixture at temperatures below 1500 K is in the form of CuF₂, which dissociates at temperatures between 1500 K and 2500 K into CuF and F. At around 3500 K CuF dissociates to give rise to atomic copper, which ionizes at higher temperatures. In the temperature range of 2000~30000 K and 0.4 MPa pressure, the mass density of the mixture is always slightly higher than that of pure SF₆.

SF₆-Cu mixture dissociation defines the variation of transport coefficients, which is influenced by temperature and pressure. In the arc channel temperature and pressure have different values and cause a heterogeneous system that increases the complexity of simulations. In the temperature range of 5000~10000 K, contaminated SF₆ has more electrical conductivity values. At temperatures higher than 20000 K, electrical conductivity curves replace their situations and the pure SF₆ curve has more values [6,7].

The other transport coefficients (viscosity, heat capacity, gas density, thermal conductivity, etc.) such as electrical conductivity depend on dissociation, and are extracted from the results of previous experimental and theoretical research [6,7] and are used as the input data for each step of the simulation.

3 Simulation results

In order to study the effects of Cu dissociation and its mixtures with SF₆ in a circuit breaker, detailed data of the circuit breaker structure is necessary. The case study is a medium voltage (33 kV, 1250 A) circuit breaker, as shown in Fig. 1. The upper contact is fixed and the lower contact is movable. When the circuit breaker opens (the worst case), the lower contact
compresses SF$_6$ gas with a 0.35 MPa initial pressure, then the gas flows between the contacts to extinguish the arc. During the contact opening, a current flows through SF$_6$ plasma arc. The arc current induces a magnetic field and Lorentz force. Joule heating serves as a heat source and gas temperature rises intensively. The arc transport coefficients, including electrical conductivity, specific heat, dynamic viscosity, and thermal conductivity, vary according to their relations with temperature, pressure and gas combination.

Based on the numerical modeling described in section 2, the calculation work is performed by using the finite element method (FEM). The whole calculation includes the stationary and transient courses. The stationary results are used as the initial state for the transient solution under the effect of the arc current. Due to the fact that arc behavior includes an electromagnetic process which is combined with a hydrodynamic process, the coupled solution method is adopted to solve the above equations. With the physical properties, source term, and boundary conditions updated, the discrete equations are formed and solved. During the simulation, the mass, momentum, and energy conservation are first solved simultaneously. After that, the electric and magnetic fields are computed according to the temperature distribution obtained before. The calculation is carried out with the sinusoidal arc current with a peak of 35000 A. Boundary conditions at the first step (closed contacts) are extracted from the case study characteristics such as: gas initial temperature (300 K), gas initial pressure (0.35 MPa), initial current chosen as 1000 A (electrode sinusoidal current magnitude equal to 35000 A) and electrode initial temperature (300 K). In addition, for the domain interfaces between gas and electrodes, a conservative interface flux is chosen.

A mesh motion model is used to simulate movable contact motion. Mesh deformation option enables the specification of node motion on the boundary or sub-domain regions of the mesh. The motion of all remaining nodes is determined by the mesh motion model, which is currently limited to displacement diffusion. With this model, the displacements applied on domain boundaries or in sub-domains are diffused to other mesh points. The diffusion is applied by the equation which determines the degree to the regions of node movement together. This equation is solved at the start of each outer iteration or time step for transient simulations, respectively. The solver calculates nodal displacements of these regions and adjusts the surrounding mesh to accommodate them. It is worth noting that the displacement diffusion model for mesh motion is designed to preserve the relative mesh distribution of the initial mesh. In the case study, the mesh motions speed (movable contact speed), time steps of simulation and simulation time are assumed to be equal to 1 m/s, 2 µs and 1 ms respectively. The model adopts physical values in which values of previous steps are chosen as initial conditions for new steps based on the number of nodes.

Furthermore, the mesh motion model is used to simulate gas inlet plate motion which compresses the gas (the plate is under the movable contact). The gas velocity in the inlets is the simulation result and is used to define it (as input data) during the contact opening (Fig. 2 and Fig. 3).
3D simulation is used to achieve accurate results. In 2D simulation one direction is eliminated from the calculation, which affects the results and accuracy. When the arc current is injected into the SF$_6$ gas, it is distributed in the X, Y and Z directions (Fig. 4). Most of the current is distribute din the Z direction, which defines the main arc behavior and produces electromagnetic force in the X and Y directions (Fig. 5). Although the amount of current in one direction is neglected in 2D simulations, its effects on the plasma deformation, electromagnetic force directions, current distribution, pinch effect and arc stability near current zero in some parts of the chamber are noticeable. To introduce the relation between current and electromagnetic force in Fig. 4 and Fig. 5, results of three directions are used which illustrate the importance of 3D analysis.

3.1 Temperature distribution

As the primary parameter of arc plasma, temperature is used to define the physical properties of plasma including electrical conductivity. Thus, the temperature distribution is significant for the calculation of electric and magnetic fields. Temperature at the edges of the contacts is higher than that at other areas. Gas temperature is reduced in these areas for SF$_6$-Cu mixtures as the result of thermal and electrical conductivity variations (Fig. 6). Because of the higher pinch effect in the middle of the arc (which causes a higher current density) and lower electrical conductivity at temperatures around 20000 K and higher (which causes higher resistivity) for SF$_6$-Cu, its temperature in the middle of the arc is higher.

Maximum values in the curves (Fig. 6) occur near the edges of the movable contact. It can be observed that temperature is considerably reduced in the region close to the contact edges in the presence of copper. The reduction of the arc temperature in the presence of copper is due to the combined effects of increased radiation loss and the cooling effect of SF$_6$-Cu. When the arc column moves, the arc current and temperature change correspondingly and the effect is observable during different steps of circuit breaker operation (Fig. 7).

The temperature reduction is in the range of 1000–2000 K which has a positive influence on the arc process. To achieve a complete conclusion, the arc is analyzed from other viewpoints in the next steps.
3.2 Electric potential

Electric potential is the function of temperature, electrical conductivity, arc current and the distance between two electrodes. Thus, it changes at different steps of movement, which is shown in Fig. 8 and Fig. 9. Electric potential in the SF₆-Cu mixture increases during the first step of circuit breaker operation and reduces during the following steps. At the first step, the SF₆ temperature increases rapidly near the fixed contact, which causes higher conductivity for SF₆ in comparison with SF₆-Cu. In addition, the current distributions for both combinations are similar and this is because of the higher compression in the arc in the initial period of application. Thus, the SF₆-Cu electric potential values are higher at the time before 2 µs (Fig. 8 and Fig. 9).

By increasing the distance between contacts and reducing arc compression, the electrical conductivity and current distribution vary coordinate. According to the coordinate changes, the electric potential values in SF₆ and SF₆-Cu become almost equal after 2 µs (Fig. 8 and Fig. 9).

3.3 Electromagnetic force density

The current that flows in the arc channel is associated with magnetic forces, which lead to an internal overpressure in the arc channel. The phenomenon is often referred to as the “pinch effect”. The total current in the column may be imagined as consisting of a number of parallel current filaments. Each separate filament will be attracted to each of the others by a magnetic force. The resulting overall force on each filament will be directed towards the center of the column. The resulting overpressure in the center of the arc column may be calculated, under the assumption that the current density \( j \) is constant over the whole cross section of the arc. With radius \( R \) the total current is \( I = \pi \cdot R^2 \cdot j \). At a radius \( r \), the magnetic field \( H(r) \) can be calculated by Ampere’s law: \( H(r) = \frac{r}{2} j \). Considering now a ring segment at radius \( r \), and with thickness \( dr \), the current that flows in this ring, in interaction with the magnetic flux, will result in a mechanical force that is at each point of the ring directed towards the center. The total current in the ring is: \( I_{\text{ring}} = 2 \cdot \pi \cdot r \cdot dr \cdot j \), and the total force (per unit of length of the ring) can be obtained as follows:

\[
F_{\text{ring}} = \mu_0 H(r) I_{\text{ring}} = \mu_0 \cdot \pi \cdot r^2 \cdot dr \cdot j^2. \tag{9}
\]

The force per unit of area is:

\[
F(r) = \frac{F_{\text{ring}}}{2\pi r} = \mu_0 \cdot \frac{r}{2} \cdot dr \cdot j^2. \tag{10}
\]

The corresponding pressure gradient can be defined as:

\[
\frac{dP}{dr} = F(r) = \mu_0 \cdot \frac{r}{2} \cdot j^2. \tag{11}
\]

The electromagnetic force density and current vary by electrical conductivity which is related to the percentage of Cu in the gas mixture. Force and current distribution values at the time before current zero define the arc stability and pinch effect (Fig. 10 and Fig. 11). Fig. 10 and Fig. 11 contain surfaces which have definite values. The software provides separated surfaces by maximum values that are isolated from the other values. The formation of surfaces at different steps can be used...
V. ABBASI et al.: The Effects of SF₆-Cu Mixture on the Arc Characteristics in a Medium Voltage Puffer GCB for finding the percentage of each value and values lower than it in each area. To compare the effects of SF₆ and the SF₆-Cu mixture on the arc at the time near current zero, electromagnetic force density surfaces with values around $1.5 \times 10^6$ kg m⁻² s⁻² and current density surfaces with values around $3 \times 10^6$ A m⁻² are illustrated in Fig. 10 and Fig. 11.

**Fig. 10** Electromagnetic force density surfaces between contacts (for values around $1.5 \times 10^6$ kg/(m²·s²)). (a) Electromagnetic force density surfaces for pure SF₆. Pinch effects occur near contacts, which are shown. The holes in surfaces illustrate less electromagnetic force values in the middle of arc channel, (b) Electromagnetic force density surfaces SF₆-Cu 10%. Continuous surfaces demonstrate more, arc stability (color online)

According to the results of the simulation (Fig. 10 and Fig. 11), it seems that the current density and electromagnetic force density for the SF₆-Cu mixture near zero current have continuous values. But the surfaces of pure SF₆ contain massive holes, which make an interruption situation more likely. At the top and bottom of the current surfaces, a continuous electromagnetic force causes constrictions in the area between contacts (the resulting net force is inwards and causes inward motions, which enhance the constriction and pinch effect for the gas mixture). The electromagnetic force constrictions near the contact edges (where extreme pinch effects occur in the areas (Fig. 10)) move the arc current forward into the contacts; this is the reason for arc stability. This phenomenon occurs at temperatures below 20000 K, because of additional electrical conductivity in the SF₆-Cu mixture. Similar investigations can be made for the other current surface levels, but the highest levels are more fundamental because of their higher electromagnetic force magnitude and their importance in forming the arc column.

**Fig. 11** Current density surfaces between contacts (for values around $3 \times 10^6$ A/m²). (a) Current density surfaces for pure SF₆ contain massive holes which reveal a higher possibility of interruption, (b) Current density surfaces for SF₆-Cu 10%. Continuous surfaces illustrate more arc stability (color online)

### 4 Conclusion

The 3D simulation of the arc in the circuit breaker has been accomplished with a realistic time-dependent description in order to predict the arc characteristics in the presence of copper and its influence on arc stability. The numerical simulation has focused on the interaction between the plasma flow and electromagnetic fields which defines arc behavior during circuit breaker operation. It is found that the presence of copper cools down the arc temperature at the region close to the contacts and has a negative effect on the current interruption due to higher electrical conductivity. Although the arc voltage is not sensitive to the presence of copper, the electromagnetic force density changes intensively to influence the arc stability and pinch effect between contacts. The current density and electromagnetic force density for the SF₆-Cu mixture near zero current have continuous values. But their values for pure SF₆ are...
discrete, which means that an interruption situation is more likely. The conclusion is a negative effect of contaminated SF₆ on arc stability. Transport coefficients variations in the mixture cause higher values of current and electromagnetic force which reduce the possibility of current interruption at zero current. Although the presence of copper cools down the arc temperature, it is not noticeable in comparison with current and force increasing.

References
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E-mail address of V. ABBASI: v_abbasi@iust.ac.ir