CO2 ARC BEHAVIOR DURING CURRENT INTERRUPTION PROCESS IN A GAS CIRCUIT BREAKER WITH EXTERNALLY APPLIED MAGNETIC FIELD

T. TAKEMATSU¹*, S. HIRAYAMA¹, T. FUJINO¹, M. ISHIKAWA¹, S. OGAWA², AND T. MORI²

¹ University of Tsukuba, Tsukuba, 305-8573, Japan, takematsu@fmm.kz.tsukuba.ac.jp
² Toshiba Corporation, Kawasaki, 210-0862, Japan

ABSTRACT

The authors conduct three-dimensional and time dependent magnetohydrodynamic numerical simulations of a gas circuit breaker model with externally applied magnetic field for CO₂ or SF₆ gas. The objective of this work is to examine the current interruption process of the gas circuit breaker model with the applied magnetic field for both gases. Numerical results show that applying the magnetic field induces swirl flow, which leads to the pressure rise in the puffer chamber for both gases. Just before second current zero, the arc forms cylindrical shape under the magnetic field for CO₂ gas unlike SF₆ gas where the arc column forms spiral shape. Arc conductance around the time is reduced by applying the magnetic field for both gases because heat convection around the arc is enhanced. This means that the thermal interruption capability can be improved by applying the magnetic field for both gases.

1. INTRODUCTION

SF₆ gas has been used as the arc interruption medium in most high-voltage gas circuit breakers (GCB). CO₂ gas is, however, considered as a possible SF₆ alternatives because the global warming potential of CO₂ gas is much smaller than that of SF₆ gas. Recently, eco-friendly gas circuit breakers using CO₂ gas have been developed (e.g., [1, 2]). Uchii et al. developed a CO₂-GCB model, and it achieved practical levels of performance for major test-duties [1]. Methods including optimization of GCB design which can use arc energy for puffer pressure rise are needed for a CO₂-GCB because the intrinsic current interruption capability of CO₂ gas is inferior to that of SF₆ gas.

The authors propose the utilization of externally applied magnetic field in a CO₂-GCB to improve current interruption capability. Under magnetic field, arc is driven by Lorentz force in a gas. As a result, convective heat transfer from the arc to a surrounding gas is expected to be promoted. This effect leads to a rise in pressure in a puffer chamber and a decrease in arc conductance.

The objective of this work is to examine arc behavior and decaying process of arc conductance under magnetic field in current interruption process for a GCB model using CO₂ gas or SF₆ gas.

2. NUMERICAL PROCEDURE

The governing equations for conservative variables are written as follows.

Mass conservation equation:

$$\frac{\partial}{\partial t} \int_V \rho \, dV + \oint_S \rho (\mathbf{u} - \mathbf{g}) \cdot \mathbf{n} \, dS = 0$$

Momentum conservation equation:

$$\frac{\partial}{\partial t} \int_V \rho \mathbf{u} \, dV + \oint_S \rho (\mathbf{u} - \mathbf{g}) \cdot \mathbf{n} \, dS = \oint_S (J \times \mathbf{B}) \, dV - \oint_S \rho \mathbf{n} \, dS + \oint_S \mathbf{r} \cdot \mathbf{n} \, dS = 0$$

Energy conservation equations:

$$\frac{\partial}{\partial t} \int_V \rho \mathbf{E} \, dV + \oint_S \rho \mathbf{H} (\mathbf{u} - \mathbf{g}) \cdot \mathbf{n} \, dS = \oint_S \kappa (\nabla T \cdot \mathbf{n}) \, dS + \oint_S (J \cdot E - \dot{q}_{rad}) \, dV$$

$$- \oint_S \rho (\mathbf{g} \cdot \mathbf{n}) \, dS + \oint_S (\mathbf{r} \cdot \mathbf{u}) \cdot \mathbf{n} \, dS$$

where \( \rho \) is the pressure, \( T \) the temperature, \( \tau \) is the viscous stress tensor. \( \mathbf{u} \), \( J \), \( E \), and...
\( B \) are the vector of the velocity, the electric current density, the electric field strength, and the magnetic flux density, respectively. \( \rho \) is the mass density, \( \dot{E} \) the total internal energy per unit mass, \( \dot{H} \) the total enthalpy per unit mass, \( \kappa \) the thermal conductivity, and \( \dot{q}_{\text{rad}} \) the radiation heat loss, respectively. \( V \) is the cell volume, \( S \) the cell surface area, \( \mathbf{g} \) the velocity vector of cell boundary, \( \mathbf{n} \) the normal unit vector. The thermodynamic properties, the transport coefficients, and the emission coefficient of SF\(_6\) and CO\(_2\) gases are formulated as a function of temperature and pressure. The numerical simulation can deal with the movement of the arcing contact and complex shapes such as puffer chamber by using Cut-Cell method [3, 4]. Eqs. (1)−(3) are solved with the finite volume method. For electrodynamics, the governing equations are written as follows.

\[
E = -\nabla \phi \tag{4}
\]
\[
\nabla \cdot \mathbf{J} = 0 \tag{5}
\]
\[
\mathbf{J} = \sigma (E + \mathbf{u} \times \mathbf{B}) \tag{6}
\]

where \( \phi \) is the scalar potential [V], \( \sigma \) the electric conductivity [S/m]. The potential differential equation derived from Eqs. (4)-(6) is discretized by the Galerkin finite element method.

The analysis object as shown in Fig. 1 is based on the SF\(_6\) rotary arc type interruption chamber used by Mori et al [5]. Time variation of arc current and the externally applied magnetic flux density assigned in this work are shown in Fig. 2, and Fig. 3, respectively. The maximum magnetic flux density on the surface of the arc-runner is about 0.14 T. Top of the movable arcing contact moves from \( x = 0.071 \) m (\( t = 0 \) ms) to \( x = 0.133 \) m (\( t = 20.05 \) ms).

On the wall surface, the non-slip wall condition is assumed. The wall temperature is set to 300 K. The electrical potential is set to 0 V on the surface of the movable arcing contact, and it is also determined to apply the setting arc current on the surface of stationary contact and arc-runner. The pressure and the temperature are set to 0.5 MPa and 300 K, respectively, for the boundary condition in the opening area (\( x \geq 0.12 \) m ). In the space filled with the working gas, the pressure and the temperature are set to 0.5 MPa and 300 K, respectively, for the initial condition. A heat energy is artificially added between the electrode gap to make a discharge path during \( t = 0-0.20 \) ms. After that, the arc current as shown in Fig. 2 is applied.

![Fig. 1 Configuration of the model arc extinguishing chamber](image1)

![Fig. 2 Time variation of arc current](image2)

3. NUMERICAL RESULTS AND DISCUSSION

Figure 4 shows three-dimensional views of the isosurfaces of \( T = 5000 \) and 10000 K at \( t = 15.0 \) ms (around the current maximum point) and \( 20.0 \) ms (just before second current-zero point). We approximately regard the isosurface of \( T = 5000 \) K as the edge of arc plasma. In Fig. 4(a) and Fig. 4(b), high temperature region (\( T \geq 5000 \) K) around the nozzle is decreased by applying the magnetic field for CO\(_2\) gas. In addition, the high temperature region is expanded on the surface of arc-runner under the applied magnetic field. These characteristics can be also confirmed in the case of SF\(_6\). Comparing Fig. 4(a) with Fig. 4(c), however, the arc forms
cylindrical shape under the applied magnetic field just before second current zero for CO$_2$ gas unlike SF$_6$ gas where the arc column forms spiral shape.

Figure 5 shows three-dimensional distributions of Lorentz force vector and isosurface of temperature $T = 5000$ K with the applied magnetic field at (a) $t = 15.0$ ms and (b) $t = 20.0$ ms for CO$_2$ gas. Lorentz force mainly works to the circumferential direction and also the strength of the force becomes weak due to a decrease in arc current from $t = 15.0$ ms to 20.0 ms. Figure 6 illustrates three-dimensional distributions of velocity vector and isosurface of temperature $T = 5000$ K with the applied magnetic field at (a) $t = 15.0$ ms and (b) $t = 20.0$ ms for CO$_2$ gas. Under the magnetic field, swirl flow is induced by circumferential Lorentz force near the surface of arc-runner. Circumferential flow velocity is getting smaller from $t = 15.0$ ms to 20.0 ms because Lorentz force becomes weak. Figure 7 shows the time variations of the pressure rise $\Delta p$ for CO$_2$ gas and SF$_6$ gas in the same puffer chamber. The sampling point of the pressure is ‘point P’ shown in Fig. 1 ($x = 1.0 \times 10^{-3}$ m, $y = 4.6 \times 10^{-2}$ m, $z = 0$ m). The reference value of the pressure is the initial value ($p = 0.5$ MPa). For both CO$_2$ gas and SF$_6$ gas, $\Delta p$ is increased by applying the magnetic field. This is caused by the swirl flows as shown in Fig. 6. $\Delta p$ for CO$_2$ gas rises up rapidly to higher level compared to that for SF$_6$ gas. Our numerical results, however, may estimate the pressure to be low comparing with the experiment using SF$_6$ gas carried out by Mori et al. [5] because the maximum pressure rise in their experiment is about 0.2 MPa for SF$_6$ gas with the same magnetic field.

Here, we evaluate heat balance by the conservation equation of thermal energy Eq. (7)
derived by the governing equation of fluid Eq. (1)–(3).
\[
\frac{\partial (\rho U)}{\partial t} = -\nabla \cdot (\rho U u) + \nabla \cdot (\kappa \nabla T) - p (\nabla \cdot u)
+ (\tau \cdot \nabla u) + \frac{J \cdot J}{\sigma} - q_{rad}
\]

In Eq. (7), \( U \) is the internal energy per unit mass [J/kg]. In the right side of Eq. (7), from top to bottom, each term expresses convection, thermal conduction, pressure work, viscous dissipation, joule heating, and radiation heat loss. Here, the heat balance per unit length along \( x \)-axis \( Q_{i,x} \) is defined as Eq. (8).
\[
Q_{i,x} = \frac{1}{x-x_i} \int_{x_i}^{x} q_i dV \quad [W/m]
\]
where \( q_i \) is the value of the \( i \)th term in the right side of Eq. (7) [W/m³], \( V \) the volume of the region where \( \sigma \geq 1 S/m \).

Figure 8 shows details of heat balances of CO\(_2\) arc plasma along \( x \)-axis just before second current-zero point (\( t = 20.0 \) ms). As shown in Fig. 8, the convection term turns from positive to negative by applying the magnetic field between arc-runner and nozzle inlet (\( x \leq 0.10 \) m). This means the convection heat loss is enhanced and it promotes a drop in arc temperature. Just before second current-zero, the convection heat loss is mainly caused by the axial flow which is produced by the pressure rise in the puffer chamber rather than the other components.

Figure 9 shows relation between the arc conductance and the arc current. For both CO\(_2\) and SF\(_6\) gas, arc conductance just before current-zero can be effectively reduced by applying the magnetic field. This is because a rapid drop in arc temperature due to the enhancement of the convection heat loss.

1) For CO\(_2\) gas, arc becomes more contracted by applying the magnetic field just before current-zero. In addition, the arc forms cylindrical shape under the magnetic field for CO\(_2\) unlike SF\(_6\) where the arc column forms spiral shape.

2) For both CO\(_2\) and SF\(_6\) gas, arc conductance just before current-zero can be effectively reduced by applying the magnetic field. This is because a rapid drop in arc temperature due to the enhancement of the convection heat loss.

### 4. CONCLUSIONS

Three-dimensional and time dependent magnetohydrodynamic numerical simulations are conducted to examine arc behavior and thermal interruption capability under the magnetic field for the gas circuit breaker using CO\(_2\) or SF\(_6\) gas. The main results are as follows:

**REFERENCES**