

Real-Time Numerical Analysis on Insulation Capability Improvement of Compact Gas Circuit Breaker

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Abstract—In order to avoid a ground fault during a large current interruption, the effect of roughness pattern inside the exhaust tube on the rapid cooling of high temperature SF₆ exhaust gas has been clarified in detail. In this study, large-eddy simulation of compressible turbulent flow under the realistic inlet conditions related to the available experimental data has been carried out. It is shown that introducing roughness pattern on the inner wall of exhaust tube is very effective for the improvement of insulation capability due to the enhanced active mixing and the flowing in of cold ambient gas from the tube exit. Finally, the computed temperature on the inner wall of exhaust tube shows a good qualitative agreement with the experimental data especially for the rough surface just after the applied transient recovery voltage.

Index Terms—Gas circuit breaker, insulation capability improvement, large-eddy simulation, rapid cooling.

NOMENCLATURE

e	Stagnant internal energy per volume [J · m ⁻³].
E	Electric field strength [V · m ⁻¹].
n	Normal coordinate.
p	Pressure [Pa].
Q_{rad}	Radiation loss [W · m ⁻³].
R	Gas constant [J · kg ⁻¹ · K ⁻¹].
t	Time [s].
T	Temperature [K].
u	Axial velocity [m · s ⁻¹].
v	Radial velocity [m · s ⁻¹].
ρ	Density [kg · m ⁻³].
τ	Shear stress [kg · m ⁻¹ · s ⁻¹].
λ	Thermal conductivity [W · m ⁻¹ · K ⁻¹].
ϕ	Electric potential [V].
Φ	Viscous dissipation [W · m ⁻³].
z	Axial.
r	Radial.
θ	Azimuthal.

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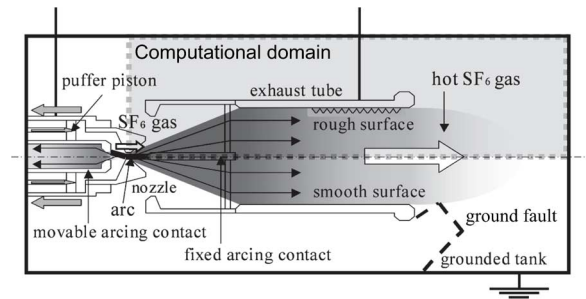


Fig. 1. Schematic illustration of a GCB and computational domain.

I. INTRODUCTION

THE large current interruption in a gas circuit breaker (GCB) has been made by applying a blast of SF₆ gas on the arc generated by separating two contacts. In recent years, for the reduction of SF₆ gas consumption and for the underground substation in a big city, research and development on the compact and high performance GCB have been energetically conducted [1]. As shown in Fig. 1, in a compact GCB, the cooling of hot exhaust gas heated by arc during current interruption is insufficient due to the small gas volume in an exhaust tube and as a consequence, it is not able to withstand the transient recovery voltage (TRV) that is applied just after current interruption. There has been reported that a ground fault may occur during the TRV in the vicinity of tube exit [2] owing to the low dielectric resistance of exhaust gas with the temperature higher than 2000 K [3], [4]. Therefore, in order to overcome this problem and to improve the insulation capability of compact GCB, it is essentially important to understand the transient behavior of SF₆ gas flow inside the exhaust tube and to realize the effective rapid cooling in a few hundreds of microseconds during current interruption.

As one of the method for the rapid cooling in exhaust tube, passive cooling by introducing roughness inside the inner surface of exhaust tube has been proposed [5]. Recently, it has been verified by the simplified model that this passive cooling by rough surface is effective for the rapid cooling of high temperature exhaust gas and also for the improvement of insulation capability [5]. In this simplified model, exhaust gas flow is assumed to be laminar and the real nozzle configuration is not included in the computational domain. Since the behavior of exhaust gas flow during a large current interruption is extremely complex due to the strong compressible and turbulent effect, it has been expected to predict the transient behavior of exhaust

gas flow and to clarify the effect of roughness on the insulation capability by more realistic model with real configuration of compact GCB.

Therefore, in this study, a real-time computational simulation on the transient thermofluid field inside the actual configuration of exhaust tube in a compact GCB has been carried out considering compressible effect and LES Smagorinsky turbulent model [6]. As for the inlet boundary condition, available experimental data [1], [7] is taken into account so as to reproduce the realistic transient cooling process inside the exhaust tube. Furthermore, in order to avoid a ground fault at TRV, the effect of roughness pattern inside the exhaust tube on the rapid cooling of high temperature SF₆ exhaust gas has been clarified in detail. The final aim of the present study is to contribute to the fundamental data for the design of high performance compact GCB.

II. NUMERICAL MODEL

A. Governing Equations

To derive the governing equations, the following assumptions are introduced in GCB model.

- 1) Plasma is optically thin and continuous in local thermodynamic equilibrium.
- 2) Plasma flow is unsteady, turbulent compressible but non-reactive.
- 3) Thermofluid field and electric field are two-dimensionally axisymmetric.
- 4) Thermodynamic and transport properties of SF₆ gas are given as a functions of temperature and pressure [8], [9].
- 5) Transient recovery voltage (TRV) is applied to the exhaust tube just at current zero, which is 24.3 after arcing contacts separation.
- 6) Melting, ablation, and deformation of exhaust tube are neglected.

In this study, large-eddy simulations (LES) of compressible flow [6] is performed to capture time-dependent turbulent behavior inside a compact GCB during current interruption. The governing equations for thermofluid field are as follows:

$$\begin{aligned} &\text{Equation of continuity} \\ &\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v) = 0 \end{aligned} \quad (1)$$

$$\begin{aligned} &\text{Equation of momentum} \\ &\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial z}(\rho u^2) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho uv) \\ &= -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \tau_{zz} + \frac{1}{r} \frac{\partial}{\partial r}(r \tau_{rz}) \end{aligned} \quad (2)$$

$$\begin{aligned} &\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial z}(\rho uv) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v^2) \\ &= -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z} \tau_{rz} + \frac{1}{r} \frac{\partial}{\partial r}(r \tau_{rr}) - \frac{\tau_{\theta\theta}}{r} \end{aligned} \quad (3)$$

$$\begin{aligned} &\text{Equation of energy} \\ &\frac{\partial e}{\partial t} + \frac{\partial}{\partial z}[(e+p)] + \frac{1}{r} \frac{\partial}{\partial r}[r \{(e+p)\}] \\ &= \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left\{ r \left(\lambda \frac{\partial T}{\partial r} \right) \right\} \\ &\quad + \Phi - Q_{\text{rad}} + Q_{\text{arc}} \end{aligned} \quad (4)$$

$$\begin{aligned} &\text{Equation of state} \\ &p = \rho RT. \end{aligned} \quad (5)$$

During the actual current interruption process, the distance between arcing contacts increases with time, however, the distance between arcing contacts, in other words, the energy input volume V by arc is kept constant for simplicity since it is not easy to simulate the movement of the contacts accurately. The energy input by arc Q_{arc} in the energy (4) is taken into account by the following relation:

$$Q_{\text{arc}} = \eta \frac{P_{\text{arc}}}{V} \quad (6)$$

where P_{arc} is arc input energy obtained by the previous experiment. The energy input efficiency η is set to 0.55 evaluated by experiments [1], [7].

To obtain the electric field at TRV of 443 kV on the exhaust tube, the following Laplace equation for electric potential ϕ is solved under electrically neutral condition

$$\frac{\partial^2 \phi}{\partial z^2} + \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} = 0 \quad (7)$$

$$E_z = -\frac{\partial \phi}{\partial z}, \quad E_r = -\frac{\partial \phi}{\partial r}. \quad (8)$$

B. Computational Domain and Boundary Conditions

Fig. 1 shows the computational domain of the GCB applied in this study. As described previously, the distance between the movable and fixed arcing contacts is kept constant for simplicity. Then, the computational domain covers the exhaust tube of GCB including nozzle region.

The time-dependent inlet conditions of velocity, temperature, and pressure are given at the nozzle inlet by referring to the actual operating conditions for real GCB as shown in Fig. 2. Note that the each maximum value is defined as 1 p.u.. The initial conditions are given as velocity of 0 m/s, temperature of 300 K and pressure of 0.6 MPa in the whole exhaust tube. The boundary conditions applied in this numerical simulation are described below.

Exhaust tube wall

$$u = v = 0 \text{ m/s}, \quad \frac{\partial T}{\partial n} = 0, \quad \frac{\partial p}{\partial n} = 0, \quad \phi = 443 \text{ kV}.$$

Grounded tank

$$u = v = 0 \text{ m/s}, \quad T = 300 \text{ K}, \quad \frac{\partial p}{\partial n} = 0, \quad \phi = 0 \text{ kV}.$$

Tank exit

$$\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0, \quad p = 0.6 \text{ MPa}, \quad \frac{\partial \rho}{\partial z} = 0, \quad \frac{\partial \phi}{\partial z} = 0.$$

Axis

$$\frac{\partial u}{\partial r} = v = 0, \quad \frac{\partial p}{\partial r} = 0, \quad \frac{\partial \rho}{\partial r} = 0, \quad \frac{\partial \phi}{\partial r} = 0.$$

III. NUMERICAL RESULTS AND DISCUSSION

A. Effect of Surface Roughness on Rapid Cooling

Fig. 3(a) and (b) shows the time evolution of exhaust gas temperature for smooth and rough surfaces, respectively. Times 0 ms and 24.3 ms correspond to the arc generation at contacts

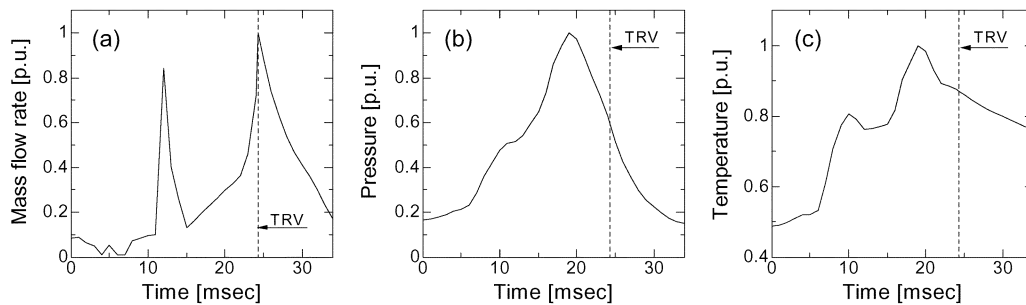


Fig. 2. Time-dependent inlet conditions. (a) Mass flow rate. (b) Pressure. (c) Temperature.

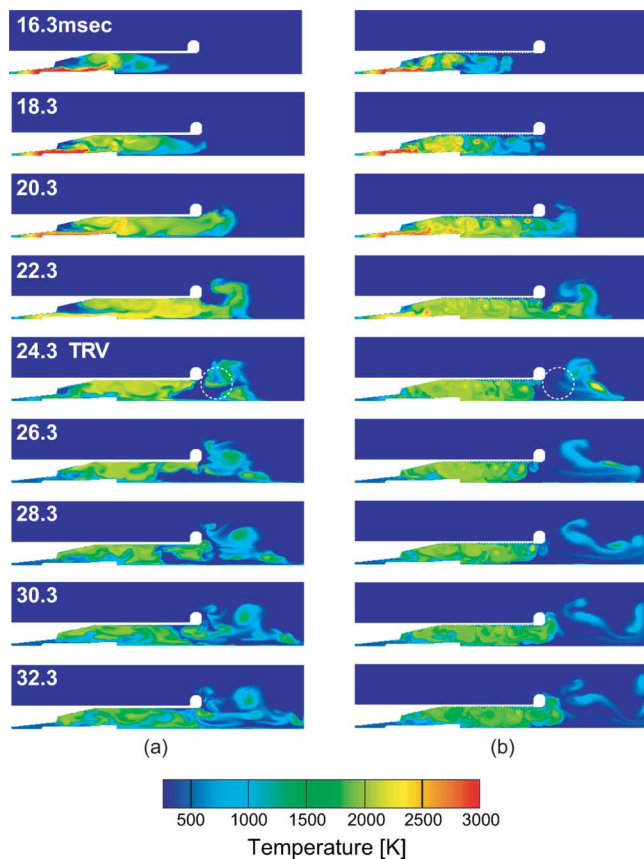


Fig. 3. Temperature evolution in a gas circuit breaker with smooth and rough surfaces. (a) Smooth surface. (b) Rough surface.

separation and imposition of TRV at current interruption, respectively. In the case of an exhaust tube with a smooth inner surface, high-temperature exhaust gas heated by arc reaches the exit of exhaust tube approximately 18 ms after the arc generation. When exhaust gas flows out of the tube, unheated ambient gas is entrained into exhaust gas flow because of a large pressure difference between exhaust gas flow and ambient gas. Then, exhaust gas flow splits and cold ambient gas flows into the exhaust tube from tube exit between 24.3 and 26.3 ms. At 24.3 ms corresponding to the imposition of TRV, the split exhaust gas with the temperature of over 2000 K approaches the exit of tube. Therefore, there is a risk of breakdown at the peak of TRV for exhaust tube with smooth surface since dielectric resistance of SF_6 becomes much lower for temperature over 2000 K. This

will be discussed in detail in the later section. The split gas flow forms a large eddy and drifts downstream at very low velocity after 26.3 ms. On the other hand, exhaust gas in the tube is again pushed out of the tube by incoming gas flow after 28.3 ms.

On the other hand, in the case of the exhaust tube with rough inner surface, separation from the surface develops as the hot exhaust gas flows inside tube from 16.3 to 20.3 ms. Then, compared to the case with smooth surface, exhaust gas is cooled down through the active mixing with a small cold eddy in the concave of rough surface. Since exhaust gas flow is accelerated due to the reduction of net effective cross section attributed to the flow separation from the inner surface of the exhaust tube, larger entrainment of cold ambient gas can be observed around 22.3–24.3 ms compared to the case with smooth surface. As a result of that, the location of split exhaust gas with the temperature of over 2000 K shifts far downstream from tube exit and then high temperature region does not appear in the vicinity of the exit of the exhaust tube at 24.3 ms. Therefore, the avoidance of a ground fault at TRV can be expected by introducing roughness on the inner surface of the tube. In the following section, this roughness pattern is referred to as standard roughness.

Fig. 4(a) and (b) shows the turbulent effect on time evolution of thermodynamic field in GCB with inner rough surface. In order to understand the turbulent effect on the rapid cooling of exhaust gas flow, numerical simulations are carried out with or without introducing turbulent model for standard roughness. By comparing these figures, the flow structures are quite different and the effect of introducing turbulent model is clearly seen especially after 24.3 ms. When the turbulent effect is considered, exhaust gas temperature becomes lower near the exit of exhaust tube at 24.3 ms corresponding to the peak of TRV. This is due to the larger inflowing of cold ambient gas from the exit of the tube. The shape of the large eddy formed in the vicinity of tube exit is quite different and the eddy is more diffusive in the case of turbulent flow. In the turbulent case, exhaust gas flows out of the tube further downstream along the configuration of exhaust tube around 30.3–32.3 ms.

Fig. 5(a) and (b) shows the effect of roughness pitch on the transient cooling process of high temperature exhaust gas. It should be noted that the amplitude of pitch is also changed in Fig. 5(a) and (b) by keeping the constant pitch angle. By increasing roughness pitch twice as large as the standard roughness, exhaust gas is more effectively cooled down due to the enhanced mixing with the larger volume of unheated gas in the concave of the rough surface around 20.3–22.3 ms. For larger

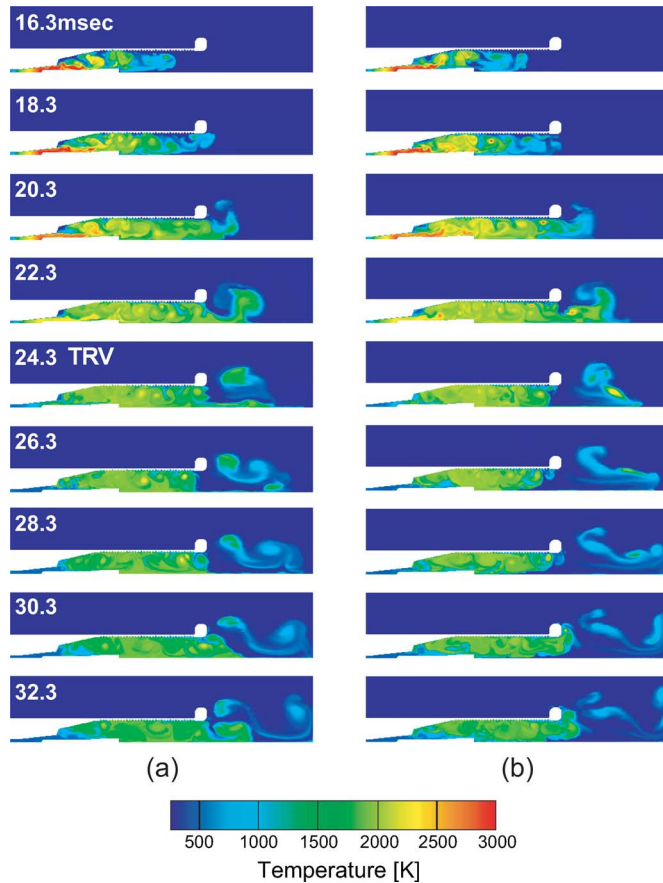


Fig. 4. Turbulent effect on time evolution of thermodynamic field in GCB with inner rough surface. (a) Laminar. (b) Turbulent.

roughness pitch, the net cross-sectional area becomes smaller due to larger separation from the inner wall, which results in higher exhaust gas velocity at tube exit. In this case, unheated ambient gas does not flow in from the tube exit because of higher momentum of exhaust gas flow. Then, exhaust gas flow does not go back in the tube and exhaust gas with the temperature of ~ 2000 K exists near the tube exit at around 24.3 ms, corresponding to the peak of TRV. This fact leads to the deterioration of insulation capability.

B. Comparison with Experimental Data

Fig. 6(a) and (b) shows the time evolution of temperature on the inner wall of an exhaust tube near the exit of the exhaust tube with smooth and standard rough surfaces, respectively. The temperature is determined from gap breakdown voltage for a small spark gap sensor [1], [7]. Although it is not shown in the figure, the same time-dependent arc input energy is given for both smooth and rough cases. Therefore, the arc duration is the same for both cases. The computed maximum temperature for smooth surface is approximately 2000 K and it is lower than the maximum measured temperature. This is because arc energy density is underestimated, since the volume of energy input by arc is kept constant throughout the simulation for simplicity. By comparing these figures, a large temperature decrease in both computed temperature and experimental data is observed just after the applied TRV for rough surface. The decrease in both

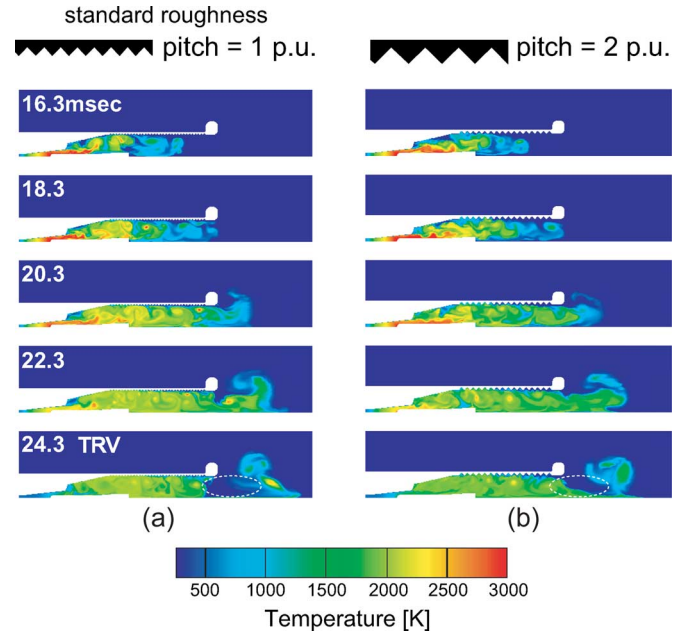


Fig. 5. Effect of roughness pitch on the transient cooling process of high-temperature exhaust gas.

measured and simulated temperatures during TRV in Fig. 6(b) is attributed to the enhanced mixing in the vicinity of wall surface and also the change in flow structure, such as separation of gas flow from the wall surface owing to the presence of roughness. There is a good qualitative agreement between the computed temperature and experimental data especially in regard to the transient cooling process after the applied TRV for the rough case. This confirms the validity of this numerical model applied in the present study.

Fig. 7 shows the computed temperature with or without turbulent effect comparing with available experimental data. Both simulated temperatures with or without turbulent effect decrease just after the applied TRV for rough surface and they agree qualitatively with experimental result. On the other hand, there is some quantitative discrepancy between the computed temperatures with or without turbulent effect especially after 25 ms and simulated temperature with turbulent effect shows better quantitative agreement with experimental result. This discrepancy results from the difference in flow structure such as larger inflowing of cold ambient gas for the rough case as shown in Fig. 4. Exhaust gas flow is expected to be highly turbulent because of the presence of roughness. Therefore, the turbulent diffusion and turbulent mixing must be considered to reproduce more realistic mixing and cooling process of exhaust gas flow during current interruption. To discuss the turbulent characteristics in detail, the quantitative evaluation of turbulent parameters should be conducted. This is one of the research topics to be done in the near future.

C. Evaluation of Insulation Capability

Fig. 8(a) and (b) shows the ratio of electric field E_f to breakdown electrical field E_{crit} at TRV for smooth and standard rough surfaces in order to evaluate the insulation capability. The breakdown electrical field is determined by calculation of

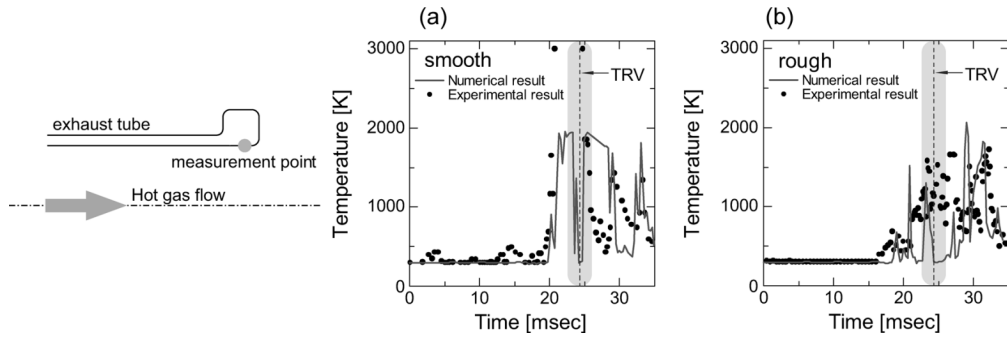


Fig. 6. Time evolution of downstream temperature on the inner wall of an exhaust tube with smooth and rough surfaces.

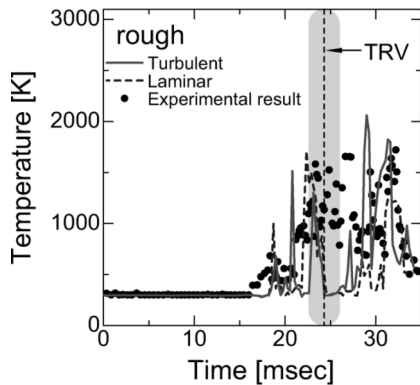


Fig. 7. Comparison between computed temperature with or without turbulent effect and experimental data.

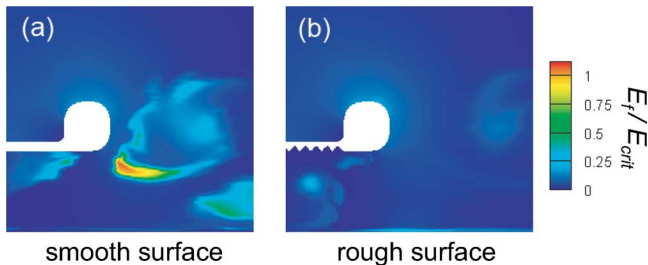


Fig. 8. Possible breakdown region for smooth and rough surfaces.

dielectric resistance of SF_6 as functions of obtained temperature and pressure [3], [8] at applied TRV. There is a larger possibility of breakdown in the region where the value of E_f/E_{crit} is greater than unity. Breakdown electrical field is estimated using local temperature and pressure at TRV obtained from numerical results. In the case of a smooth surface, E_f/E_{crit} becomes greater than unity in the vicinity of the exit of the exhaust tube. This shows there is a larger possibility of breakdown at TRV. On the other hand, in the case of a rough surface, the high-temperature region does not appear in the vicinity of tube exit due to the effective cooling and by changing transient flow pattern as explained in Section III-B. As a result of that, the ratio becomes less than unity in the whole region. Therefore, it is clearly shown that roughness pattern inside the exhaust tube is the effective way for the insulation capability improvement of a compact GCB.

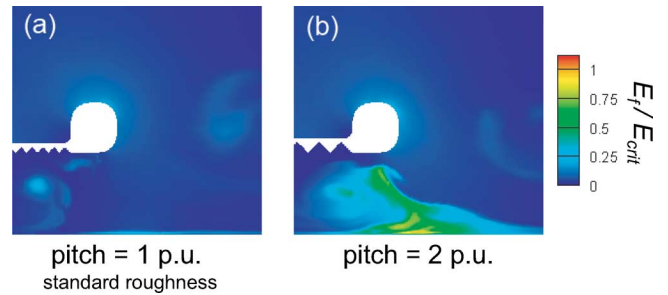


Fig. 9. Effect of roughness pitch on the possible breakdown region.

Fig. 9(a) and (b) shows the effect of roughness pitch on the improvement of insulation capability for roughness pattern optimization. In the case of larger roughness pitch, the value of E_f/E_{crit} becomes closer to unity due to the presence of exhaust gas with the temperature of ~ 2000 K in the vicinity of tube exit. The highest value of E_f/E_{crit} for larger roughness is ~ 0.8 in the vicinity of axis.

Therefore, in order to improve the insulation capability of a compact GCB, it is very important to enhance active mixing with unheated gas in the concave of roughness surface and also to induce the flowing in of the cold ambient gas from tube exit at the applied TRV by optimizing the configuration of the roughness pattern.

IV. CONCLUSION

In order to avoid a ground fault during a large current interruption, the effect of roughness pattern inside the exhaust tube on the rapid cooling of high-temperature SF_6 exhaust gas has been clarified in detail by carrying out a real-time computational simulation under realistic operating conditions. The obtained results by computational simulation can be summarized as follows.

- 1) By installing roughness pattern on the inner surface of exhaust tube in a compact GCB, exhaust gas with the temperature of over 2000 K is pushed away from the vicinity of the tube exit where a ground fault is reported to occur during TRV. This is due to the enhanced transient cooling, separation of gas flow from the inner surface of the exhaust tube and cold ambient gas backflow from tube exit. As a result of that, the possible breakdown region is significantly suppressed, therefore, it is clearly shown that roughness

pattern is the effective way for the insulation capability improvement of a compact GCB.

- 2) There is a good qualitative agreement between the numerical and experimental temperature near the exhaust tube exit especially in regard to the transient cooling process after the applied TRV. This confirms the validity of this numerical model.
- 3) Compressible turbulent effect needs to be considered to reproduce more realistic mixing and cooling process of exhaust gas flow during current interruption.
- 4) In order to improve the insulation capability of a compact GCB, it is very important to enhance active mixing and also to induce the flowing in of cold ambient gas from the tube exit at the applied TRV by optimizing roughness pattern.

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