PREDICTION OF PRESSURE RISE BUILD-UP IN A SELF-BLAST HIGH VOLTAGE CIRCUIT BRAEKER USING CFD SIMULATION

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ABSTRACT

Self-blast circuit breakers utilize the energy dissipated by the arc itself to create the required conditions for arc quenching when the current is zero. The arc at the high current phase induces nozzle ablation, which causes the pressure to rise inside the circuit breaker. During the interrupting process of the circuit breaker, the pressure in the thermal chamber is characterized as one of the physical parameters of performance. To develop the circuit breaker simulator, various tests for measuring pressure have been carried out by testing the circuit breaker through varying the volume of the thermal chamber, nozzle and stroke speed. The measured pressure values from pressure rise test are compared with the results obtained from computational fluid dynamics (CFD) to validate the simulator code.

1.INTRODUCTION

A gas circuit breaker (GCB) is an electrical power facility essential for the protection of a substation from fault current and to supply reliable power electricity. When the fault current is detected, a self-blast circuit breaker operates its switching process. In this process, SF6 gas inside the self-blast circuit breaker becomes extremely high pressure and temperature in a few milliseconds using arc energy and extinct arc between two contacts. It is hard to measure and analyze the accurate performance of the internal flow of the gas because the arc has transient and complex physical phenomena that include the radiation of the arc. This affects the flow of SF_6 gas and PTFE ablation.

In order to understand these complex physical phenomena, it is necessary to adopt a numerical analysis technique. Numerical analysis is also used to measure and predict the gas flow inside a circuit breaker. Furthermore, it is important to understand the complex physical phenomena of an arc with accurate predictions. It is vital to design and fabricate more reliable and cost effective circuit breakers. To analyze the complex gas and arc phenomena inside the circuit breaker, one of the most effective and widely used tools is CFD.

This paper will show various tests using the testing circuit breaker that vary the volume of the thermal chamber, nozzle, and stroke speed while a high current is applied. The pressure from the thermal chamber is then measured using the pressure sensor until the arc is extinguished. The measured pressure is compared with the pressure results obtained from CFD and the numerical analysis model is verified.

2. EXPERIMENTAL SET-UP

This study fabricated the SF_6 gas self-blast circuit breaker. As shown in Figure 1, the testing circuit breaker was able to vary the volume of the thermal chamber, nozzle and stroke speed by simply changing specific parts while applying a current of up to 50kA. In order to easily change the parts, the assembly and disassembly process was considered for only the minimum parts necessary. As shown in Figure 1, a piezoelectric pressure sensor was installed to measure the pressure build up inside the circuit breaker. The sensor was insulated with Teflon insulators to minimize the effect of the voltage applied.

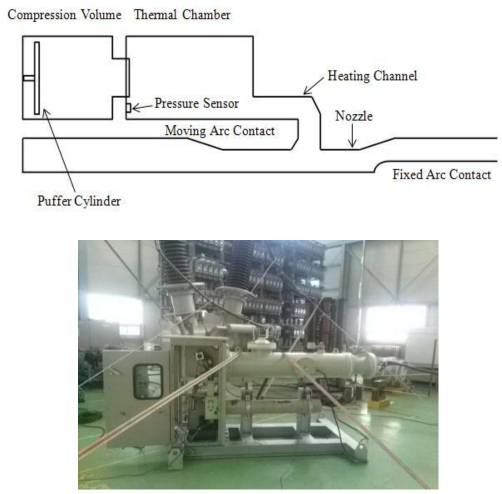

Figure 1. Schematic geometry with the pressure sensor and the actual testing circuit breaker

3. NUMERICAL ANALYSIS

Numerical analysis of arc includes complex physical phenomena such as convection, conduction, radiation, turbulence of gas and nozzle ablation. When the circuit breaker operates, the gas pressure thermalized with SF6 and PTFE in time order of 10^{-9} seconds and this is short time for diffusion or convection time [1]. Accordingly, a local thermodynamic equilibrium (LTE) is assumed to analyze the arc plasma and the ablation of the circuit breaker. While applying LTE assumption, the numerical analysis of arc behavior is described by rotationally symmetric Navier-Stokes equations including the Lorentz force with momentum, Ohmic heating, and radiation loss as the sources in the energy equation. The general governing equation can thus be described as

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

where ρ is the density, V is the velocity vector, $\emptyset$ is the dependent variable, Γ is the diffusion coefficient and S_{φ} is the source term. The last three terms are described in Table 1[2].

Table 1. The dependent variable, source term and diffusion coefficient for Equation (1)

Equation	$\emptyset$	Γ	S_{φ}
Continuity	1	0	0
z-momentum	w	$\mu+\mu_t$	S_w
r-momentum	v	$\mu+\mu_t$	S_v
enthalpy	h	$(k+k_t)/c_p$	S_h

By neglecting the gravitational force, the source term from Table 1 is described by the equations given below.

$$S_w = -\frac{\partial \mathrm{P}}{\partial \mathrm{z}} + (\mathbf{J}\times\mathbf{B})_z \qquad (2)$$

$$S_v = -\frac{\partial \mathrm{P}}{\partial \mathrm{z}} + \frac{1}{r}\frac{\partial}{\partial \mathrm{r}}\left\{\mathrm{r}(\mu+\mu_t)\frac{\partial \mathrm{v}}{\partial \mathrm{r}}\right\} + \frac{\partial}{\partial \mathrm{z}}\left\{(\mu+\mu_t)\frac{\partial \mathrm{w}}{\partial \mathrm{r}}\right\} - \frac{2\mu v}{r^2} + (\mathbf{J}\times\mathbf{B})_r \qquad (3)$$

$$S_h = \frac{\partial \mathrm{P}}{\partial \mathrm{t}} + \sigma E^2 - q + \Phi \qquad (4)$$

where Φ is the viscous dissipation and can be described by

$$\Phi = \frac{1}{r}\frac{\partial}{\partial \mathrm{r}}\left\{\mathrm{r}(\mu+\mu_t)w\frac{\partial \mathrm{w}}{\partial \mathrm{r}}\right\} \qquad (5)$$

The source term is calculated by solving current continuity equation and electric potential equation is expressed by

$$\nabla\cdot(\sigma\nabla\varphi) = 0 \qquad (6)$$

where φ is the electrical potential. Subsequently, the electric field and joule heating terms are calculated using the following equations.

$$\vec{\mathbf{E}} = -\nabla\varphi \qquad (7)$$

$$\vec{J} = -\sigma\cdot\vec{E} \qquad (8)$$

In equation (4), q represents the net radiation loss per unit volume and time. In order to calculate q, a simple model was used assuming a monotonic radial temperature profile. T_{max} is described as the maximum arc plasma temperature and the arc region is defined from the arc axis to $0.83T_{max}$, R_{83} at a radial position at temperature 4000K, R_{4000K}. The arc radius is defined as $0.5(R_{4000K}+R_{83})$ [3].

In this analysis, it was assumed that 50% of the radiation flux from the arc core to the arc radius is absorbed and that the remaining radiation flux from arc is ablated to the nozzle [4]. According to Ruchti and Niemeyer's theory [5], the temperature required to break the PTFE into PTFE vapor is 3400K. The PTFE vapor enters into a flow with a temperature of 3400K±200K.

Furthermore, the mass flux of PTFE vapor at the nozzle is described as

$$F_m = \frac{I_n}{H_v} \tag{9}$$

where I_n is the radiative flux at the nozzle and H_v is the enthalpy of the PTFE with a value of 1.19×10^7 *J/kg*[5]. To reduce the calculation time, the Prandtl mixing length model is applied to calculate the turbulent flow model [6]. For CFD simulation, the internal pressure is initialized to 6.5 *bar* and the internal temperature is set up to 300 *K*. The study of Frost and Liebermann [7] is used to generate a high temperature and pressure property of SF_6 gas.

4. COMPARISON OF EXPERIMENT AND SIMULATION RESULTS

When the fault current is detected, the self-blast circuit breaker operates and electrodes are separated. At this moment, the electrical arc is created while increasing the pressure and temperature of the surrounding SF_6 gas. This high pressured SF_6 gas flows into the thermal chamber. Ablation of PTFE nozzle occurs due to radiation from the electrical arc. This process significantly affects the pressure build up and flows into the thermal chamber [8]. The relatively cold gas in the thermal chamber is mixed with the hot gas from the arc region and the mixed gas flows back into the arc region. The arc is blown with the mixed gas and extinguishes at a current of zero.

The experiments and simulation results show the pressure measurements of the thermal chamber according to different conditions of arcing time and nozzle shape. To analyze the interruption process numerically, CFD was used and compared with the experimental results.

As shown in Figure 2, the measured pressures are compared at three different arcing times, such as 8ms and 13ms. The results show a strong correlation between measurements and numerical solutions. From the numerical analysis, the calculated peak pressures and the measured peak results show agreement within a 7% error.

The pressure was measured in the thermal chamber by choosing two different nozzle throat lengths. The results of these measurements are shown in Figure 3. Nozzle B has a nozzle throat that is approximately 30% longer than Nozzle A. These two comparisons show that Nozzle B has a higher pressure build-up in the thermal chamber than Nozzle A.

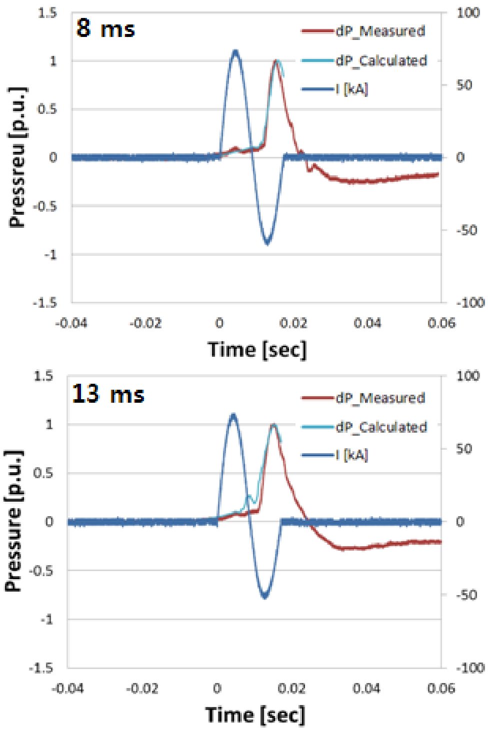

Figure 2. Comparison of the measured and experimental results by different arcing time

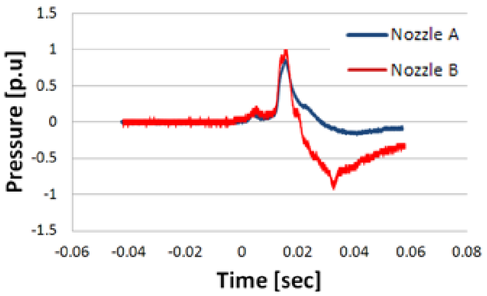

Figure 3. Measured pressure results according to different nozzle throat lengths.

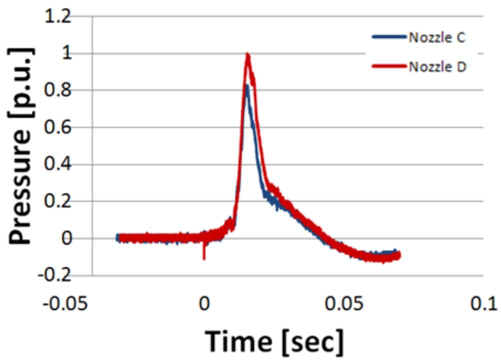

Figure 4. Measured pressure results according to different nozzle downstream shapes.

The pressure build-up results were compared according to the shape of the nozzle downstream. For Nozzle C, the downstream diameter increases after the nozzle throat for a small amount and the rest of the downstream diameter remains the same. For Nozzle D, which has the same nozzle throat length, the downstream diameter continues to increase at a less steep rate than Nozzle C until the end of nozzle. As shown in Figure 4, the pressure build-up in the thermal chamber increases more when Nozzle D is installed. Figure 5 shows the comparison results of the measured and calculated results of nozzles C and D. The graphs are showing the good agreement with numerical analysis. By measuring the pressure with different shapes of the nozzle, this study has been able to evaluate how the shapes of the nozzle affect the peak pressure of the thermal chamber.

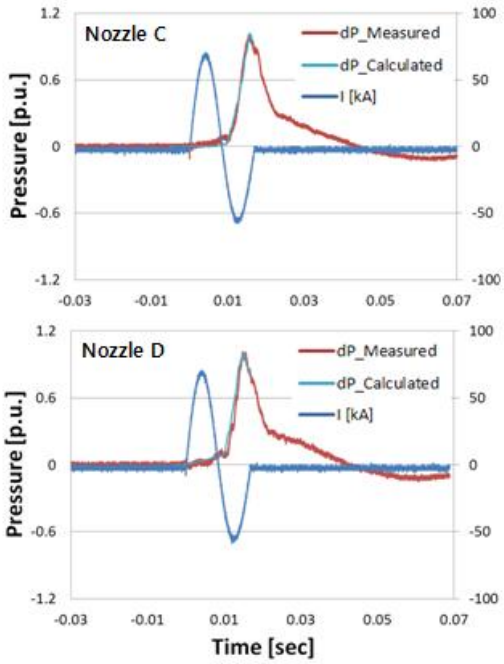

Figure 5. Comparison of measured and calculated results according to different nozzle shape

5. CONCLUSION

This study compared experiment results with CFD simulation to verify numerical analysis. A self-blast testing circuit breaker was fabricated to easily change the volume of the thermal chamber, nozzle and arcing time without disassembling the entire circuit breaker. A comparison was made between the data obtained after testing the circuit breaker and the CFD simulation. Comparing the measurements and the simulated results showed a good agreement with a small error.

According to the numerical analysis and experiments, many physical phenomena such as the volume of chamber, nozzle geometry, nozzle material, and arcing time influence the pressure build-up. In order to improve the numerical analysis of the interruption process, further studies on these factors are required.

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