Fundamental Research on SF$_6$-free Gas Insulated Switchgear
Adopting CO$_2$ Gas and Its Mixtures

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Abstract: Fundamental properties of CO$_2$ gas and its mixtures as an arc quenching and insulating medium for a high-voltage power equipment were investigated theoretically and experimentally. It was noted that “self-blast” technique utilizing arc energy effectively to enhance puffer pressure is a good solution for a CO$_2$-applied gas circuit breaker (CO$_2$-GCB) because of its relatively small heat capacity and high arc voltage. A 72 kV-31.5 kA class CO$_2$-GCB model was designed, produced, and it showed satisfactory performance for major test-duties. In addition, a life cycle assessment (LCA) was carried out to evaluate the environmental contribution by applying CO$_2$ gas as an alternative medium. An LCA calculation based on the developed CO$_2$-GCB model reveals that it could reduce the global warming impact compared to the latest SF$_6$ gas circuit breaker in the considered life cycle scenario. Furthermore, CO$_2$-based environmentally-benign gas mixtures, such as CO$_2$/O$_2$, were also investigated. Some kinds of additional gases might increase arc-quenching and/or insulating performance compared to that of pure CO$_2$ gas.

Keywords: SF$_6$ gas, CO$_2$ gas, mixture, gas insulated switchgear(GIS), gas circuit breaker(GCB), global warming

1. INTRODUCTION
SF$_6$ gas has widely been used for a high-voltage electric power equipment such as a gas insulated switchgear (GIS) and a gas circuit breaker (GCB) due to its excellent insulating and arc-quenching capability. Although SF$_6$ gas strongly contributes to achieve compactness and high reliability of the equipment, it has been recognized as one of the potent global warming gases and was designated to reduce the emissions at COP3 in Kyoto in 1997. At present, strategic effort to reduce the emissions is being made, which actually proves effective.[1] Over the long term, however, it is certainly preferable to reduce the consumption itself, because its atmospheric life time is observed to be quite long, thus the amount of SF$_6$ gas on the earth will inevitably get increasing in the future unless artificial destruction.

With the above background, the authors focus on CO$_2$ gas as an alternative medium of SF$_6$ gas, which has very low global warming potential compared to SF$_6$ gas (1/23,900). Fundamental properties of CO$_2$ gas as an arc-quenching and insulating medium were investigated theoretically and experimentally. Based on these findings, a 72 kV-31.5 kA class CO$_2$ gas circuit breaker (hereinafter called CO$_2$-GCB) model was designed, produced, and tested. As a result of current interruption and dielectric insulation tests, the CO$_2$-GCB model achieved practical levels of performance for major test-duties.

In addition, a life cycle assessment (LCA) was carried out to evaluate the environmental contribution by applying CO$_2$ gas as an alternative medium. An LCA calculation based on the developed CO$_2$-GCB model reveals that it could reduce the global warming impact by about 45% compared to the latest SF$_6$ gas circuit breaker in the considered life cycle scenario.

Furthermore, the authors also investigated some CO$_2$-based environmentally-benign gas mixtures such as CO$_2$/O$_2$. These additional gas(es) might increase arc-quenching and/or insulating performance compared to that of pure CO$_2$ gas. In the present paper, some experimental results will be briefly introduced.

2. WHY CO$_2$ GAS?
The gases that are applicable to an environmentally-benign electric power equipment are required to have no or minimal toxicity, global warming effect and ozone depletion effect, and should remain gaseous at low temperatures, for example, around -30 °C. When selecting the alternative gases widely from the above viewpoints, the possible candidates are narrowed down to air, N$_2$, O$_2$, H$_2$, CO$_2$, rare gases (He, Ar, etc), and their mixtures.[2] In practice, they are also required to have adequate insulating and arc-quenching capability, chemical stability, and have no flammability and explosiveness. Eventually, the possible candidates that can be applied as single gas or main gas of mixture could be limited only to N$_2$ and CO$_2$. (Here, air is regarded as an N$_2$-based mixture.) Although CO$_2$ is recognized as one of the representative global warming gases, it can be considered applicable as far as power equipment application because the gas amount for this use is negligible little compared with the globally concerned amount.[3]

Table 1 shows the comparison of fundamental gas properties of SF$_6$, CO$_2$ and N$_2$. As shown in Table 1, CO$_2$ meets the basic requirements for application to an environmentally-benign electric power equipment. In addition, CO$_2$ has a lower boiling temperature than SF$_6$, and it is known that CO$_2$ remains gaseous at low temperature ranges down to -40 °C even at a high gas pressure of 1.0 MPa-abs.
Table 1. Comparison of fundamental gas properties between SF$_6$, CO$_2$ and N$_2$.

<table>
<thead>
<tr>
<th>Gas</th>
<th>SF$_6$</th>
<th>CO$_2$</th>
<th>N$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular mass</td>
<td>146.06</td>
<td>44.01</td>
<td>28.01</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>5.9</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>GWP$^*$</td>
<td>23,900</td>
<td>1</td>
<td>~0</td>
</tr>
<tr>
<td>ODP$^*$</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Toxicity$^*$</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Chemical stability</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>Flammability / Explosibility</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Boiling temperature (°C)$^*$</td>
<td>–51</td>
<td>–78</td>
<td>–198</td>
</tr>
<tr>
<td>Dielectric strength (%)$^*$</td>
<td>100 (–)</td>
<td>34 (–)</td>
<td>25 (+)</td>
</tr>
<tr>
<td>Arcing time constant (μs)$^*$</td>
<td>0.8</td>
<td>15</td>
<td>220</td>
</tr>
</tbody>
</table>

$^*$ At 300 K, 1 atm
$^*$ Global Warming Potential, Integrated period 100 years (IPCC, 1995)
$^*$ Ozone Depletion Potential
$^*$ As pure gas (Note that arc-ed gas could be different)
$^*$ At 1 atm
$^*$ 50% breakdown voltage measured by a full-scale coaxial cylindrical electrode(4)(The weak polarity value is shown), Lightning impulse, At 0.9 MPa-abs
$^*$ Measured for a free-burning arc at 1 atm

As for insulating capability, as also shown in Table 1, CO$_2$ is naturally lower than SF$_6$, but its 50% breakdown voltage is about 35% higher than that of N$_2$ at a high gas pressure of 0.9 MPa-abs.[4]

In Table 1, arc-quenching capability is evaluated by arcing time constant as an index for thermally interrupting capability of a gas. Qualitatively, smaller arcing time constant suggests better thermal interrupting capability. Table 1 shows that the arcing time constant of CO$_2$ is higher than that of SF$_6$, but is below one tenth of that of N$_2$.

In short, although CO$_2$ gas is inferior to SF$_6$ gas in insulating and arc-quenching capabilities, it surpasses N$_2$ gas which is regarded as a representative alternative gas in many previous works, particularly in arc-quenching capability. This suggests that CO$_2$ gas is a promising alternative gas, particularly for switching apparatus such as a GCB.

3. CO$_2$ GAS AS AN ALTERNATIVE MEDIUM FOR A CIRCUIT BREAKER

3.1. Basic features

Arc-quenching capability of a gas itself can be estimated to some extent from the arc time constant shown in Table 1. Specifically, arc-quenching capability of CO$_2$ gas is considered between SF$_6$ gas and N$_2$ gas. As known generally, the higher blasting pressure toward arc around a current zero leads the higher thermal interruption performance. This means, higher blasting pressure is necessary for CO$_2$ gas to interrupt the same current in the same condition compared to SF$_6$ gas.

On the other hand, a puffer-blast-type GCB widely disseminated nowadays must be designed so that puffer pressure keeps necessary level for a successful interruption around a current zero for every required arcing time condition. Thus, as far as considering a puffer-blast-type GCB, puffer pressure build-up characteristic during a current interruption process is a fundamental factor, as well as the arc-quenching properties of the gas itself.

Fig. 1 shows puffer pressure waveforms during a current interruption for both CO$_2$ gas and SF$_6$ gas obtained with the same current condition and the same puffer-type interrupter. As seen obviously in Fig. 1, the puffer pressure of CO$_2$ gas rises up rapidly to higher level compared to SF$_6$ gas. This is due to small heat capacity $\rho C_v$ (where $\rho$, $C_v$ represent density, specific heat at constant volume, respectively) and higher arc voltage (i.e. larger energy input to the arc) of CO$_2$ gas, which is basically preferable property especially for a short arcing time condition. By the other hand, Fig. 1 also indicates puffer pressure of CO$_2$ gas decreases faster compared to SF$_6$ gas. This is mainly due to higher sound velocity of CO$_2$ gas, which causes faster pressure leakage from the puffer cylinder. This fact implies inferior interruption performance in a long arcing time condition. To maintain high levels of puffer pressure even in a long arcing time condition, it can be considered that larger puffer cylinder volume would be necessary when adopting CO$_2$ gas. Consequently, for a puffer-type interrupter using CO$_2$ gas, both larger puffer cylinder volume and higher puffer pressure rise are conflictingly necessary, which leads larger driving energy, size, higher cost, and so on.

To avoid these as well as possible, puffer-type interrupter with “self-blast” technique could be a good solution. “Self-blast” means puffer-pressure enhancing technique by utilizing arc energy effectively. Self-blast technique is known to be effective for SF$_6$ gas, but it can be considered more effective for CO$_2$ gas, because of its smaller heat capacity and higher arc voltage, which enables to get higher pressure more easily by self-blast process.

The authors focus on Hybrid-puffer$^\text{TM}$ technique, one of the self-blast-type interrupters.[5] Fig. 2 shows the analytical result of the puffer pressure rise at current zero, compared between a conventional double-flow-type and Hybrid-puffer$^\text{TM}$-type interrupters for both CO$_2$ and SF$_6$. As noted in Fig. 2, Hybrid-puffer$^\text{TM}$ brings about higher puffer pressure rise at current zero throughout the considered arcing time condition for both SF$_6$ gas and CO$_2$. 

![Fig. 1. Difference of puffer pressure properties between SF$_6$ gas and CO$_2$ gas during a current interruption. (Measured in 28.4 kA interruption)](image-url)
Fig. 2. Comparison of puffer pressure enhancing effect by Hybrid-puffer™ technique between SF₆ and CO₂.

gas, but it can be seen more apparently for CO₂ gas case, which suggests Hybrid-puffer™ technique is more effective for CO₂ than SF₆ as expected.

3.2. Development of 72 kV-31.5 kA CO₂-GCB model

Based on the basic investigations of CO₂ properties, a 72 kV-31.5 kA class CO₂-GCB model, shown in Fig. 3, was designed and produced. The specifications of the model are shown in Table 2. The filling gas pressure is 0.8 MPa-abs, which is a little higher than that of a usual SF₆-GCB. In practical use of a CO₂-GCB, however, the filling gas pressure could be higher, for example 1.0MPa-abs, in consideration of gas liquefaction, safety, and related regulations. In the CO₂-GCB model, a Hybrid-puffer™-type interrupter specially designed for CO₂ gas was adopted. Furthermore, all the dimensions of the GCB components were determined based on fundamental dielectric data of CO₂ gas with sufficient margin. The tank diameter is about 1.7 times as large as that of the latest SF₆-GCB in the same rating.

Current interruption and insulation tests of the CO₂-GCB model were carried out based on the standard of IEC 62271-100. The test results are summarized in Table 3. As shown in Table 3, the CO₂-GCB model achieved satisfactory performance for major test-duties; namely, capacitive current switching, short-line fault 90%, terminal fault 100% (symmetrical and asymmetrical) interruption, power-frequency and lightning impulse insulation.

Decomposed products and gases after current interruptions are also one of the fundamental issues from the practical viewpoint. It was observed that no harmful arced gas which cannot be absorbed by Zeolite and that no controversial decomposed product for the practical use were detected even after more than 10 times large current interruptions.[3]

4. ENVIRONMENTAL IMPACT ESTIMATION BY A LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is known as a means evaluating environmental burdens quantitatively in the “cradle-to-grave” life cycle of a product. An LCA study was carried out to evaluate the environmental contribution of the CO₂-GCB model shown in Fig. 3.

Fig. 4 shows the considered life cycle flow and the conditions of the LCA, and the result is shown in Fig. 5. It was noted from Fig. 5 that the contribution due to materials is larger for the CO₂-GCB than the SF₆-GCB, but contribution due to gas leakage is extremely low for the
CO_2_ gas and CO_2/O_2_ gas mixture cases succeeded in interruption, but the post arc current of the two gases were obviously deferent, showing much smaller in the case of CO_2/O_2_ gas mixture. In other words, admixture of 15% O_2_ gas causes reduction of post arc current, which implies that adding O_2_ gas could make decaying rate of arc conductivity faster.

Another remark is concerned with decomposed product generated by arcing. In a large current interruption with pure CO_2_ gas, brownish powder product was generated, and it was proved from elemental analysis by an X-ray micro analyzer that the powder contained free carbon although it seemed very slight. When mixing 15% O_2_ gas, on the other hand, decomposed product changed whitish, and no carbon peak was detected. This result suggests that O_2_-rich atmosphere seems to reduce free carbon generation that might deteriorate dielectric reliability.

Dielectric properties of CO_2/O_2_ gas mixture were also investigated. The 50% lightning impulse breakdown voltages of pure CO_2_ gas and CO_2(80%)/O_2(20%) gas mixture were obtained by up-down method at 1.1 MPa-abs with coaxial cylinder electrode system with a conductor diameter of φ120 mm and a tank diameter of φ300 mm. As a result, admixture of 20% O_2_ gas brings about 17% increase of breakdown voltage compared to pure CO_2_ gas.

6. CONCLUSIONS

The authors focus on CO_2_ gas as an alternative medium of SF_6_ gas, which has very low global warming potential compared to SF_6_ gas (1/23,900). Fundamental properties of CO_2_ gas and its mixtures as an arc quenching and insulating medium were investigated theoretically and experimentally. The conclusions are listed below:

1) It was found that “self-blast” technique utilizing arc energy effectively to enhance puffer pressure is a good solution for a CO_2-GCB because of its relatively small heat capacity and high arc voltage. A 72 kV-31.5 kA class CO_2-GCB model, which does not contain SF_6_ gas at all, was designed, produced, and tested. In this model, a Hybrid-puffer interrupter specially designed for CO_2_ gas was adopted. The tank diameter is about 1.7 times as large as that of the latest SF_6-GCB in the same rating. As a result of current interruption and dielectric insulation tests, the CO_2-GCB model showed satisfactory performance for major test-duties.

2) A life cycle assessment (LCA) was carried out to evaluate the environmental contribution by applying CO_2_ gas as an alternative medium. An LCA calculation based on the developed CO_2-GCB model reveals that it could reduce the global warming impact by about 45% compared to the latest SF_6_ gas circuit breaker in the considered life cycle scenario.

3) Admixture of appropriate gas(es) to CO_2_ gas might increase arc-quenching and/or insulating performance compared to pure CO_2_ gas. CO_2/O_2_ gas mixture was adopted as one example, and it was noted that admixture of O_2_ gas caused reduction of post arc current in the short-line fault interruption, and also increase of lightning impulse breakdown voltage com-
pared to pure CO$_2$ gas.

REFERENCES