Fundamental Research on SF_6-free Gas Insulated Switchgear Adopting CO_2 Gas and Its Mixtures

Toshiyuki Uchii[1], Yoshikazu Hoshina[1], Hiromichi Kawano[1]
Katsumi Suzuki[1], Tetsuya Nakamoto[1] and Mitsuru Toyoda[2]

1. Power and Industrial Systems R&D Center, Toshiba Corporation, Kawasaki, Japan
2. Hamakawasaki Operations, Toshiba Corporation, Kawasaki, Japan

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.

Corresponding author: T. Uchii, toshiyuki.uchii@toshiba.co.jp

Table 1. Comparison of fundamental gas properties between SF_6, CO_2 and N_2.

Gas	SF_6	CO_2	N_2
Molecular mass	146.06	44.01	28.01
Density (kg/m^3)*1	5.9	1.8	1.1
GWP*2	23,900	1	~0
ODP*3	–	–	–
Toxicity*4	–	–	–
Chemical stability	Stable	Stable	Stable
Flammability / Explosibility	–	–	–
Boiling temperature (°C)*5	–51	–78	–198
Dielectric strength (%)*6	100 (–)	34 (–)	25 (+)
Arcing time constant (μs)*7	0.8	15	220

*1 At 300 K, 1 atm
*2 Global Warming Potential, Integrated period 100 years (IPCC, 1995)
*3 Ozone Depletion Potential
*4 As pure gas (Note that arced gas could be different)
*5 At 1 atm
*6 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
*7 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.

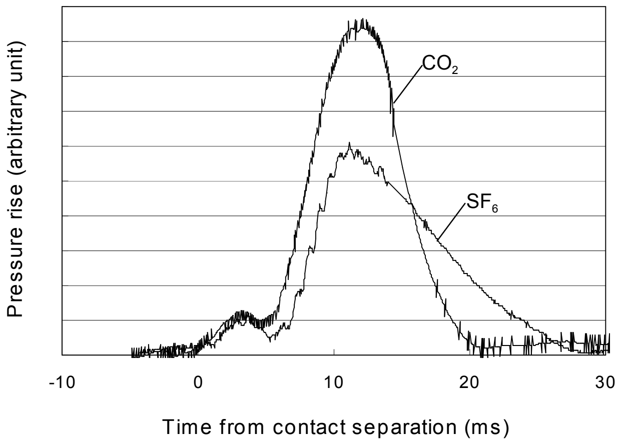


Fig. 1. Difference of puffer pressure properties between SF_6 gas and CO_2 gas during a current interruption. (Measured in 28.4 kA interruption)

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 ρC_V (where ρ, 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. On 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™ 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™-type interrupters for both CO_2 and SF_6. As noted in Fig. 2, Hybrid-puffer™ brings about higher puffer pressure rise at current zero throughout the considered arcing time condition for both SF_6 gas and CO_2

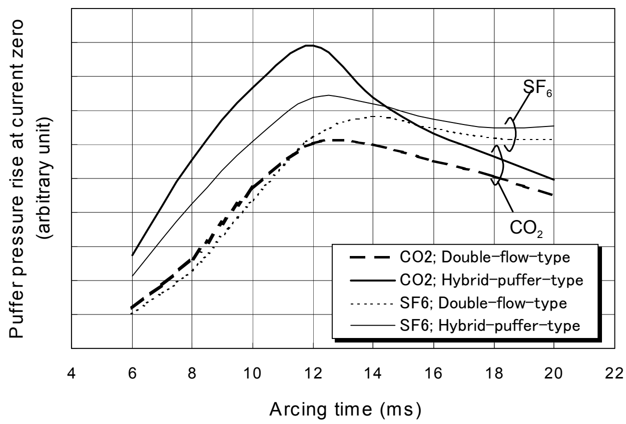


Fig. 2. Comparison of puffer pressure enhancing effect by Hybrid-puffer™ technique between SF_6 and CO_2.

gas, but it can be seen more apparently for CO_2 gas case, which suggests Hybrid-puffer™ technique is more effective for CO_2 than SF_6 as expected.

3.2. Development of 72 kV-31.5 kA CO_2-GCB model

Based on the basic investigations of CO_2 properties, a 72 kV-31.5 kA class CO_2-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 SF_6-GCB. In practical use of a CO_2-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 CO_2-GCB model, a Hybrid -puffer™-type interrupter specially designed for CO_2 gas was adopted. Furthermore, all the dimensions of the GCB components were determined based on fundamental dielectric data of CO_2 gas with sufficient margin. The tank diameter is about 1.7 times as large as that of the latest SF_6-GCB in the same rating.

Current interruption and insulation tests of the CO_2-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 CO_2-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

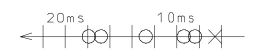
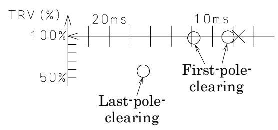
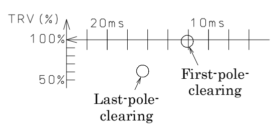
Life cycle assessment (LCA) is known as a means evaluating environmental burdens quantitatively in the “cradle-to-grave” life cycle of a product. An LCA study was carried out to evaluate the environmental contribution of the CO_2-GCB model shown in Fig. 3.

Fig. 3. View of the 72 kV-class CO_2-GCB model (for single phase).

Table 2. Specifications of the CO_2-GCB model.

Items	Value
Filling gas	CO_2 100%
Filling gas pressure	0.8 MPa-abs
Rated voltage	72 kV
Rated interrupting current	31.5 kA
Power frequency	50 Hz
Rated ACWV	140 kV_{rms}
Rated LIWV	350 kV

Table 3. Summary of the test results of the CO_2-GCB model. (O: Success, X: Failure)

RATINGS	72.5 kV-31.5kA-50Hz	
STANDARD	IEC 62271-100	
DUTY	RESULT	JUDGEMENT
Capacitive current switching (After 3 times 60% current interruptions)	NO Restrike during 16 times interruptions around the minimum arcing time with the recovery voltage of 1.7 x 72.5kV/1.73.	Satisfactory
Short line fault 90% (L90)	Arcing time:  20ms 10ms	Interruption window: 9.5 ms secured Satisfactory
Breaker terminal fault 100%, Symmetrical (T100s(b))	Arcing time:  TRV (%) 100% 50% 20ms 10ms First-pole-clearing Last-pole-clearing	Interruption window: 3.3 ms for first-pole-clearing, 8.2 ms secured over all. Satisfactory
Breaker terminal fault 100%, Asymmetrical (T100a) (Major loop)	Arcing time:  TRV (%) 100% 50% 20ms 10ms First-pole-clearing Last-pole-clearing	Interruption window*: 3.6 ms for first-pole-clearing, 8.0 ms secured over all. Satisfactory
LI insuration	375 kV No F.O.	Satisfactory
AC insulation	160 kV_{rms} No F.O.	Satisfactory

*Minimum arcing time for minor loop is assumed from T100s

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 CO_2-GCB than the SF_6-GCB, but contribution due to gas leakage is extremely low for the

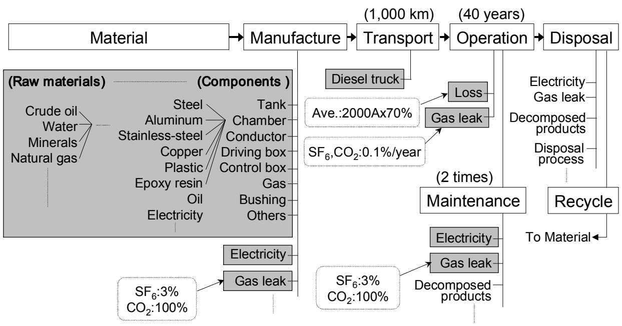


Fig. 4. Considered life cycle flow and conditions of the LCA.

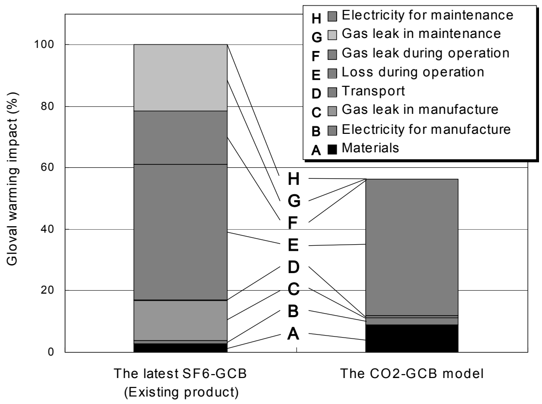


Fig. 5. Reduction of global warming impact during 40 years operation by the CO_2-GCB model.

CO_2-GCB. As a whole, the CO_2-GCB model could reduce the global warming impact by about 45% compared to the latest SF_6-GCB in the same rating for 40 years operation including two maintenance opportunities.

5. POSSIBILITY OF CO_2-BASED GAS MIXTURES

One of the strategies to improve performance of a CO_2-applied switchgear may include admixture of appropriate gas(es) to CO_2 gas. Needless to say, that additional gas must be environmentally-benign one, which is apparently a kind of natural origin gases as described in chapter 2. Adding extra gas(es), arc-quenching and dielectric properties of the gas naturally change, and it is expected in some cases that the current interruption and/or the insulation capabilities could improve.[6,7] The authors focus on CO_2/O_2 gas mixture here as one example, and introduce some experimental findings below.

The arcing time constant of O_2 gas is known to be relatively small, specifically 1.5 μs whereas 0.8 μs for SF_6 gas, 15 μs for CO_2 gas, 220 μs for N_2 gas for a free-burning arc.[8] This fact implies O_2 gas would have preferable arc-quenching capability than CO_2 gas. Pure O_2 gas, however, could not be applied as an alternative gas, because of its supportive flammability and strong corrosivity. The authors, therefore, adopted CO_2(85%)/O_2(15%) gas mixture, and gave it a trial in a short-line fault 90% interruption with a current of 28.4 kA (90% of 31.5 kA) and a surge impedance of 450 Ω by using the CO_2-GCB model shown in Fig. 3. Both pure 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(EDX) 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.

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