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High-Voltage Switchgear Technology Applying CO_2/O_2 Natural-Origin Gas Mixture as an Alternative Insulating and Interrupting Medium to SF_6

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SUMMARY

The present paper describes key properties of CO_2/O_2 gas mixture as an alternative to SF_6 for switchgear applications and the findings through large numbers of full-scale tests performed in the168 kV prototype development, from the viewpoints of gas performance, design, gas handling and lifetime aspects. Captured and repurposed CO_2's neutral global warming potential and respectable insulating and arc quenching properties make it a promising candidate to replace SF_6. The addition of O_2 proves many benefits not only from the viewpoint of performance (e.g. insulation, interruption and temperature rise), but also the viewpoints of safety gas handling and lifetime aspects. In particular, an optimized ratio of 70% CO_2 and 30% O_2 represents a well-balanced feasible solution that shows no inherent drawbacks that cannot be overcome by design optimization.

KEYWORDS

Gas-insulated switchgear (GIS), Circuit breaker, Global warming, SF_6 emission, Natural-origin gas (NOG), CCUS (Carbon dioxide Capture, Utilization and Storage), CO_2/O_2 gas mixture

1 Introduction

Environmental performance is the motivating factor to pursue SF_6 (Sulphur Hexafluoride) alternatives. SF_6 was first targeted for emission reduction by the 1997 Kyoto protocol. Since then, the industry has taken two parallel paths [1]. First, SF_6 emissions reduction through design, manufacturing and operating improvements. And second, the research and development of SF_6 alternatives which are able to meet the performance and reliability expected of modern substation equipment. As an alternative to SF_6, CO_2/O_2 natural-origin gas mixtures offer the inherent characteristics necessary to meet both environmental and performance goals [1-4].

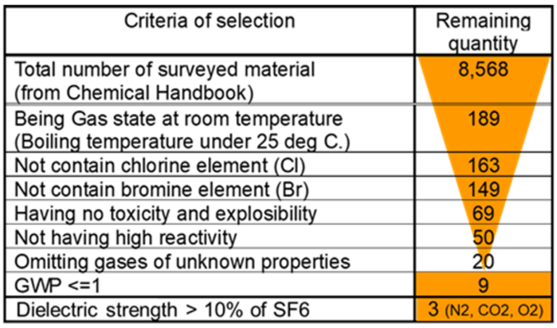
The present paper describes key properties of CO_2/O_2 gas mixture as an alternative to SF_6 for switchgear applications and the findings through large numbers of full-scale tests performed in the168 kV prototype development, from the viewpoints of gas performance, design, gas handling and lifetime aspects.

2 Performance of CO_2/O_2 gas mixture and optimized mixture ratio

2.1 Screening of practical alternative gases for switchgear applications

SF_6 is well known as an excellent electrical insulator and arc quenching medium. When searching for an alternative, we must consider all inherent physical characteristics and how those may be applied to produce economical and reliable equipment designs.

When screening gases from a list of 8,568 general materials, considering the fundamental requirements from the practical viewpoint of a high-voltage dielectric gas, the possible candidates that can be used as a single gas or a main gas of a mixture are eventually narrowed down to only three gases; namely N_2, CO_2 and O_2, as shown in Figure 1[1]. It can be noted here that the selected gases (N_2, CO_2 and O_2) are all natural-origin ones. CO_2 is one of the representative global warming gases, but it should be noted that this application is rather a CCUS (Carbon dioxide Capture, Utilization and Storage) and does never generate brand-new CO_2 on the earth.



Criteria of selection	Remaining quantity
Total number of surveyed material (from Chemical Handbook)	8,568
Being Gas state at room temperature (Boiling temperature under 25 deg C.)	189
Not contain chlorine element (Cl)	163
Not contain bromine element (Br)	149
Having no toxicity and explosibility	69
Not having high reactivity	50
Omitting gases of unknown properties	20
GWP <=1	9
Dielectric strength > 10% of SF6	3 (N2, CO2, O2)

Figure 1: Screening of practical alternative gas that can be used as a single gas or a main gas of a mixture for high-voltage equipment application. [1]

2.2 Fundamental characteristics of CO_2/O_2 gas mixtures

The 'ideal' alternative solution should have equivalent functionality, safety, reliability, and economic potential as well as environmental superiority. Any of the proposed SF_6 alternatives so far include their inherent pros and cons for those points. It is important to consider whether the disadvantage(s) will be potentially solved by future improvements in design technology or not (in other words, whether the disadvantage(s) is determined by only the inherent properties of the gas or not). From this point, Table 1 summarises fundamental characteristics of CO_2/O_2 gas mixtures in two categories; namely "fixed characteristics" and "design influenced characteristics". As seen in Table 1, CO_2/O_2-based solutions should be essentially feasible because there are no disadvantages which cannot be solved by design improvement, i.e. no disadvantage determined by only the inherent properties of the gas. On the other hand, equipment size adopting natural-origin gases (NOG) will be ineluctably larger than that with SF_6 or other artificial fluorinated gas based on the same design scheme because of lower dielectric strength of the gas. These disadvantages, however, could be potentially overcome with design technology improvements as well-demonstrated in the history of the past SF_6 technological developments.

Table 1: Fundamental characteristics of CO_2/O_2 gas mixture (○ Advantage, ■ Disadvantage)

Fixed characteristics	Design influenced characteristics
o GWP <1. o ODP=0. o Free of artificial fluorinated gas. Possible to be released into atmosphere. [10] o Lower condensation temperature even at elevated pressure. [4,11] o High thermal stability, low decomposition. [4,11] o Common industrial gas. Simple gas handling is well established. [12]	▪ Lower dielectric strength (approx. 35%) at equivalent pressure than SF_6. Dielectric strength depends on pressure, mixture ratio and condensation temperature; e.g. CO_2/O_2(30%) at -50 deg.C condensation has approx. 80% dielectric strength of SF_6 at -30 deg.C condensation. [4] ▪ Lower switching performance than SF_6. Thermal interruption performance of CO_2 is approx. 60% of SF_6, and higher blasting pressure and addition of O_2 lead to better switching performance. CO_2 is much better than N_2 or air in terms of switching performance. [4,11] ▪ Lower heat transfer than SF_6. Practically approx. 120% of SF_6 temperature rise. [4] o Typically much less toxic decomposed products after arcing compared to those in SF_6. [4,12]

2.3 Optimized mixture ratio of CO_2/O_2

A gas mixture with 70% CO_2 and 30% O_2 (hereafter called "CO_2/O_2(30%)") represents a well-balanced feasible solution that shows no inherent drawbacks that cannot be overcome by design. The addition of O_2 minimizes the formation of conductive free Carbon (soot) such that with accumulated fault duty, the internal solid insulation will remain viable for the lifetime of the equipment. In a closely related topic, O_2 drastically reduces the permanent decomposition of CO_2 by more than an order of magnitude, and consequently contributes to keep toxicity negligibly low [5]. (Details will be discussed later)

The addition of O_2 improves cold dielectric strength [4,6,7], leading to more compact designs with reduced operating energy. Figure 2 illustrates the influence of O_2 mixed with CO_2. One might expect the dielectric strength to follow a linear-type mixing rule with O_2 concentration (blue line) but, in fact, will have a nonlinear relationship (red curve). In part, this explains the desire to increase O_2 concentration above that which will simply reduce arc by-product contamination (~10%). Note in Figure 2 the departure of the actual dielectric strength from linear reaches a maximum at approximately 30% O_2 concentration. Above 30% the difference is stable and above 50% begins to reduce until intersection at 100%. Therefore, we take advantage of O_2 dielectric strength improvement up to 30% concentration. More than 30% concentration has a high cost in long-term material compatibility with little gain in performance improvement.

The addition of O_2 improves interruption and switching performance as well [4]. Duties such as capacitive switching benefit from improved cold dielectric strength as mentioned in the previous discussion. The capacitive switching duty typically defines the opening speed (kinetic energy) and therefore a large component of the opening energy required from the operating mechanism. Interruption duties such as short line fault also see improvement from the addition of O_2 [4]. Since these faults always define the maximum pressure (compression energy) required from the interrupter, any reduction allows the possibility to reduce operating energy. The cumulative effect of reduced operating energies, both kinetic and compression, is the improvement of long-term reliability.

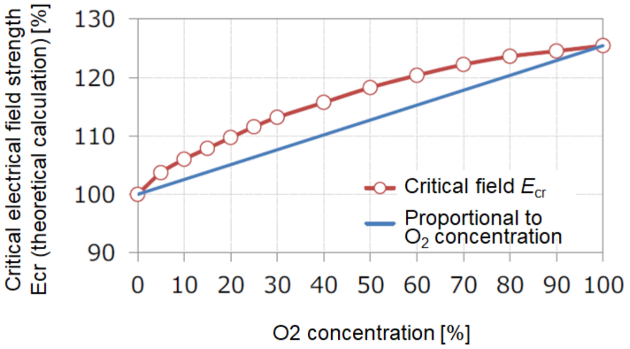


Figure 2: Effect of O_2 concentration on dielectric strength in CO_2.

3 Gas Handling and Lifetime Aspects

3.1 CO_2/O_2 gas mixture handling

For the sake of simplicity and safety, the authors' preference is to provide premixed bottles of CO_2/O_2(30%) for equipment filling. Transportation of gas cylinders will be identical to SF_6 since both carry the same US DOT HAZMAT classification of 2.2 in the US and similar. Through coordination with gas handling equipment manufacturers, existing gas handling equipment is basically suitable to work with CO_2/O_2(30%) gas mixture following some upgrades. For example, gas filtration and drier media should be replaced, rubber hoses should be checked for compatibility with O_2 service, and pressure gauges and regulators should be checked and upgraded. Otherwise, the main components such as compressors, storage tank, etc. are suitable for both the proposed mixture and pressure schemes. Heating and/or mixing of CO_2/O_2 is not required prior to filling the equipment.

Filling procedures are similar to SF_6 since the equipment utilizes the same type of temperature compensated density switch but with redesigned internal mechanisms and switch settings to account for the temperature - pressure behaviour of the gas mixture and the pressure scheme. Since CO_2 and O_2 are both natural-origin gases and inexpensive, new gas and possibly even used gas may be released into the atmosphere during maintenance work with filtering before discarding due to the presence of arc by-products.

3.2 Material compatibility

The long-term compatibility of internal parts with O_2 is considered as part of the technology development. These include not only general metal oxidation but also lubricants, coatings, surface treatments, adsorbents, contacts and seals. Figure 3 shows some examples of how to validate entire systems of lubricants and coatings in long-term aging tests. The general approach is to use SF_6 as the baseline for comparison and subject test coupons to thousands of hours at elevated temperature. As the tests progress, colour, viscosity and adhesion are monitored in both the test gas and SF_6. No significant issue has been confirmed for CO_2/O_2.

Contact systems of base metal, plating and lubricant are validated in a similar manner except that in addition to the above criteria, contact resistance is also monitored and recorded approx. every 1,000 hours. Selecting suitable plating material for the CO_2/O_2 gas mixture, it is confirmed that contact resistance has been keeping practically stable in the ongoing test.

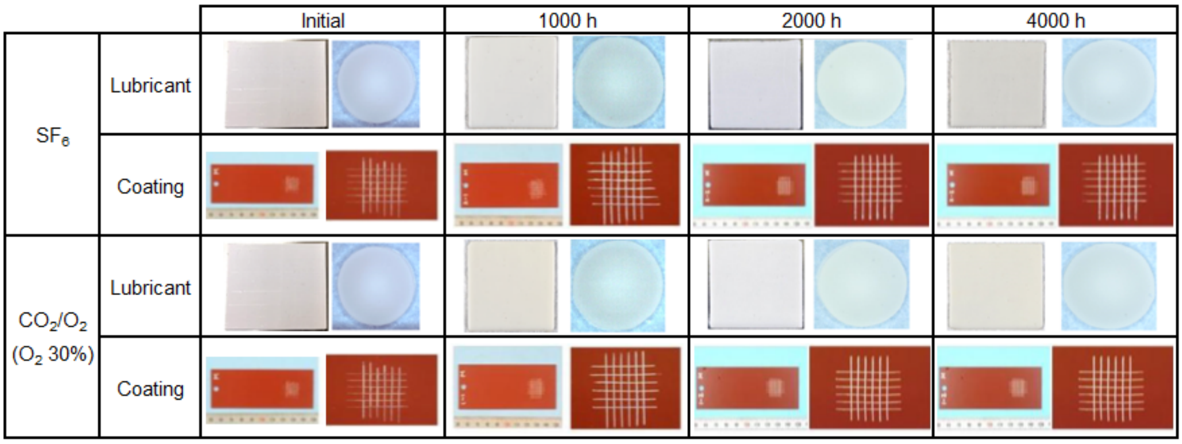


Figure 3: Examples of long-term material compatibility test (lubricants and coatings).

3.3 CO_2/O_2 gas sealing

Compared to SF_6, CO_2 is highly permeable in most elastomeric sealing compounds including the common compounds used in SF_6 equipment. In addition to permeability, long-term aging is another concern which must be addressed to ensure adequate gas tightness over the lifetime of the equipment. A new elastomeric seal is relatively soft, resilient and exhibits no permanent deformation when unloaded. On the other hand, an aged seal may show signs of stiffening, embrittlement and permanent deformation when unloaded. Aging may be influenced by several operational parameters such as material strain, temperature and atmosphere (O_2 sensitivity). As shown in Table 2, successful and long-lived seal system is possible with CO_2/O_2(30%) gas mixture by proper compound selection (Material D), groove design and temperature control. Regarding gas detection, since CO_2 and O_2 are both very common gases widely used in e.g. refrigeration equipment, food industries, and so forth, various kinds of detectors and concentration monitoring instruments are available, some of which are applicable for monitoring and leak detection for the present application.

Table 2: Comprehensive research of sealing compounds applicable to CO_2/O_2 gas mixture.
(OO: Excellent, O: Good enough, (O) Acceptable, X: Not acceptable)

Compound	Permeation	Temperature maximum	Temperature minimum	Lifetime (Compression set)	O_3 resistance	Embrittlement
Target spec.	Equivalent to common one used for SF_6	90 deg.C	-25 deg.C	> 30 years	Acceptable in actual breaker circumstances	No significant sign
Material A	X	O	O	O	O	O
Material B	O	O	O	(O)	X	X
Material C	O	OO	O	O	O	X
Material D	O	OO	O	O	O	O

3.4 Erosion of nozzle and contact due to arcing

Particularly for a gas circuit breaker, erosion rates of PTFE nozzle and W/Cu arcing contact materials are the important factors to determine how durable it is over repetitive current interruption stresses. Figure 4 shows the comparison of erosion rates among different O_2 concentrations, which was experimentally obtained after 12 times heavy current interruptions in the range of 23 to 29 kA with a pressure of 0.8 MPa-abs. As seen in Figure 4, erosion rate of the plug contact was almost equivalent and those of the nozzle and the tulip contact were both lower with higher O_2 concentration. Physical interpretations of these experimental outcomes require very complicated analysis due to the dynamic and transient nature of the phenomena, but at least it is fair to say that additional O_2 up to at least 30% did not cause any significant negative effect on erosion of PTFE nozzle and W/Cu arcing contact materials.

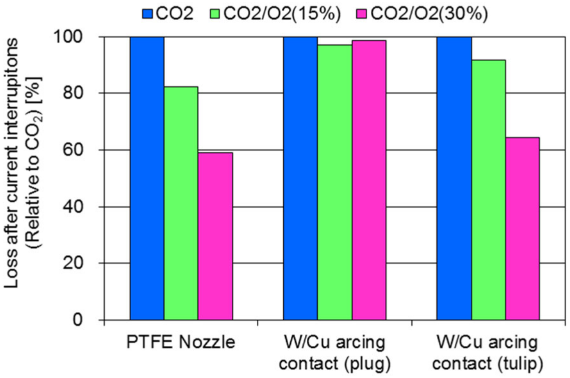


Figure 4: Comparison of erosion rates of PTFE nozzle and W/Cu arcing contact materials among different O_2 concentrations.

3.5 Decomposed gases and solid by-products due to arcing

Decomposed gases and solid by-products generated by discharge, especially high-power arcing, are also important from the EHS point of view as well as functionality of the equipment. Table 3 summarizes the decomposed gases detected in 490 liter enclosure after 1,500 kJ of arc energy for both pure CO_2 gas and CO_2/O_2(30%) gas mixture cases, together with the acute toxicity criteria LC50(4 hour). The relevant decomposed gases are CO, HF* and O_3 (*slight H and F come from humidity and PTFE nozzle ablation, respectively). In other words, it is these three decomposed gases that should be noted in CO_2/O_2 gas mixture application, even though abnormally massive arc energy was injected into the enclosure in a short period in this case, compared to actual operations. It is readily seen in Table 3 that 30% O_2 drastically reduces CO generation. HF and O_3 are also a concern but should be managed with suitable absorbent as has been well proven with traditional SF_6 switchgears. Figure 5 shows how well a suitably selected absorbent works for all the three concerned gases.

In a laboratory test, the authors recommend (i) to release arced CO_2/O_2 gas mixture directly into the open air (normally, only filtering solid by-products if necessary before discarding, not necessary to implement special treatments), (ii) to monitor CO_2 and O_2 concentration in a testing room against suffocation and CO_2 poisoning (a handy, inexpensive detector is commercialized and available from many vendors) and (iii) to display a caution around the outlet of the venting hose to keep personnel away from it. Normally, once arced CO_2/O_2 is released into the open air, it immediately becomes well diluted below the LC50 criteria.

As for solid by-product, it may influence not only EHS but also quality and reliability of the equipment since some conductive substance may threaten sound insulation capability [8]. The images of the by-products after 1,900 kJ accumulative interruptions in pure CO_2 gas and CO_2/O_2(30%) gas mixture are shown in Figure 6. It was revealed by X-ray analysis that solid by-product due to high power arcing consists of mainly metal oxides and possibly slight carbon (soot). As shown in Figure 6, colour of the by-product was obviously changed with O_2 content, that is, it became whitish whereas dark-brownish in the pure CO_2 case, suggesting less carbon generation. Actually, the CO_2/O_2 breaker model withstood +/-390 kV (T10 TRV waveform, 5 times for each polarity) without any problem.

(Unit: ppmV)

	Toxicity LC50	Pure CO_2	CO_2/O_2(30%)
CO_2	141,618 /4h	(Balance)	(Balance)
O_2	-	196	299,880
CO	2,612 /4h	7,000	120
HF	642 /4h	100	250
O_3	11 /4h	35	25
H_2	> 15,000/1h	15	4
CH_4	> 500,000/2h	2	2

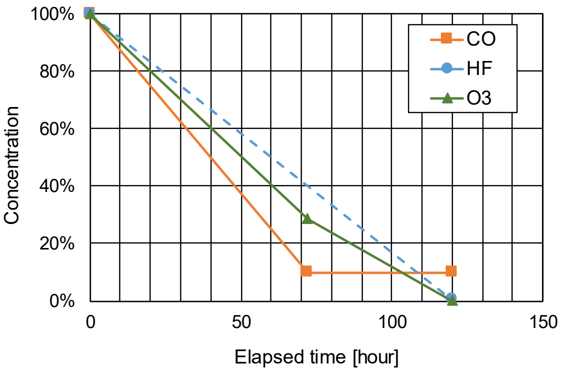


Table 3 (Left): Decomposed gases detected after arcing in pure CO_2 and CO_2/O_2 gas mixture.

Figure 5 (Right): Reduction of decomposed gas concentrations CO_2/O_2 gas mixture with a specific absorbent.

Pure CO_2
(Dark-brownish)

CO_2/O_2(30%)
(Whitish)

Figure 6: Solid by-products after arcing in pure CO_2 gas and CO_2/O_2 gas mixture after 1,900 kJ accumulative interruptions.

3.6 Impact of gas mixture composition dispersion on performance

As discussed in Table 3, changes in CO_2 and O_2 concentration are proved to be very limited, practically almost no change as seen in Table 3, even after multiple heavy fault interruptions. However, certain range of dispersion in mixture composition must exist in reality due to gas handling processes and potential uncertainties of % measurement instruments. It is of importance from the practical point of view to assess its impact on performance and take into account it in hardware design. Here, supposing +/-3% change in O_2 concentration in CO_2/O_2(30%) gas mixture as a rather conservative number, its impact on dielectric performance is evaluated. As shown in Figure 7, even with this conservative condition, the impact is limited in the range of +/-1%, which is well manageable by a design role. Furthermore, this fact may be quite beneficial for asset management because it suggests the possibility that, just similar to SF_6 equipment, only filling pressure monitoring should be normally sufficient (no need to measure all concentration of mixture components) for CO_2/O_2 gas mixture equipment.

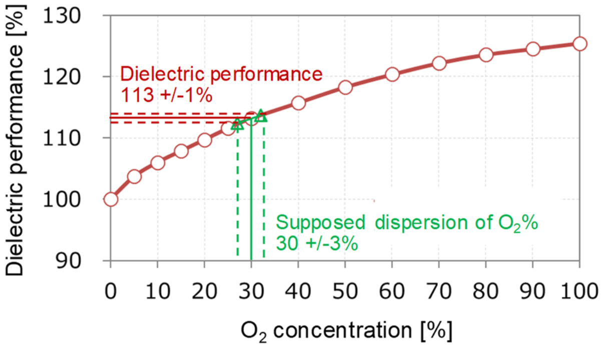


Figure 7: Impact of O_2 % dispersion on dielectric performance of CO_2/O_2 gas mixture equipment.
(Supposing dispersion of 30 +/-3%)

3.7 Gas toxicity

As new gas, SF_6, CO_2 and CO_2/O_2(30%) are all considered Category 6 (relatively harmless) on the Hodge-Sterner acute toxicity scale [9]. During development testing, the authors have the opportunity to measure the decomposed gases of fault interruption, as discussed in Chapter 3.5, and assess the acute toxicity of the gas considering abnormal accident or end of life. Figure 8 shows these results for a 490 liter enclosure after 1,500 kJ of arc energy. For a 40 kA rating, 1500 kJ is considered to represent the 90th percentile of lifetime arc energy and is approximately equivalent to 9 times of 100% terminal faults. Figure 8 clearly shows the positive effect of O_2 addition to CO_2. The acute toxicity level of CO_2/O_2 starts lower and uniquely stays in Category 6 even after 1,500 kJ of multiple heavy fault interruptions.

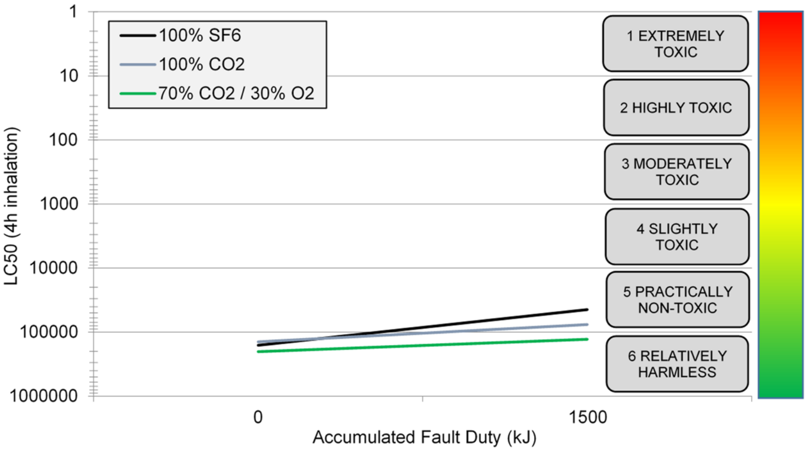


Figure 8: Acute toxicity assessment: Accumulated fault duty vs. LC50(4h) on Hodge-Sterner scale, up to 1,500 kJ in 490 liter enclosure.

3.8 CO_2/O_2 gas mixture flammability

Extensive fault testing has been performed with CO_2/O_2(30%) gas mixtures. Despite the presence of 30% O_2 and a strong ignition source (high current arc) no residual burning or explosion has ever occurred. In this manner, it has been experimentally demonstrated that materials commonly used for switchgear applications, like fluorine resins (PTFE nozzle) and metals of Al, Fe, Cu, W and so forth, show no problem in CO_2/O_2(30%) gas mixture, in which proper attention should be paid not to use an irregular organic material close to a hot interrupting part. During the development process, all manner of breakdown occurs while searching for the design limits; namely faults across the arcing and main contacts, ground faults and faults across solid insulation, etc. including abnormally long arcing times. Under no circumstances these breakdowns led to an uncontrolled or sustained continuation of the arc.

Figure 9 is the experimental assessment result of the flammable range of a combustion gas CH_4 in CO_2/O_2 [13]. It demonstrates the fact that CH_4 concentration lower than 5% never cause combustion even for any O_2 concentration, and also O_2 concentration lower than 20% never cause combustion even for any CH_4 concentration, which supports the experience in a number of CO_2/O_2 breaker testing.

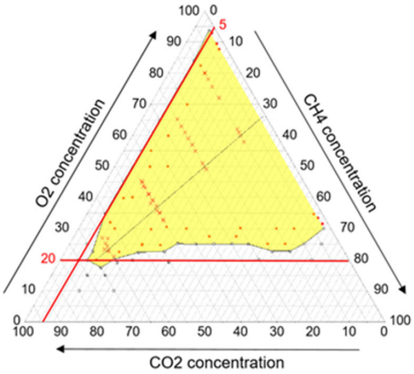
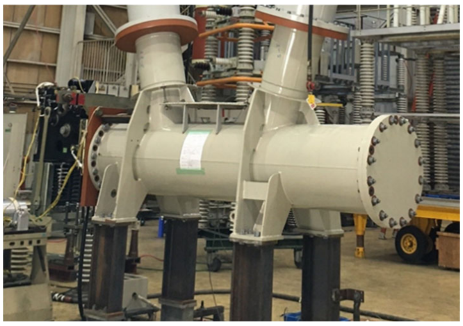


Figure 9: Experimental assessment result of flammable range of a combustion gas CH_4 in CO_2/O_2 (yellow area indicates the flammable range). [13]

4 Prototype design of a CO_2/O_2 breaker

CO_2/O_2 gas mixtures can be used for both insulating and arc-quenching media for circuit breakers and other GIS equipment, where working principle is basically the same as modern SF_6 switchgears. Figure 10 shows a 168 kV CO_2/O_2 circuit breaker (prototype), in which CO_2/O_2(30%) 2-component gas mixture was filled at 0.8 MPa-g to comply with the Japanese high-pressures gas safety code. The working principle of the interrupter was similar to typical SF_6 circuit breakers (i.e. thermal assisted puffer) with proper design adaptations based on physical properties of CO_2/O_2. A well-proven spring operating mechanism used for existing SF_6 gas circuit breakers was applied from the viewpoints of reliability and cost. The 168 kV prototype breaker shown in Figure 10 achieved satisfactory performance in a series of tests covering the relevant JEC, IEC and IEEE standards, which demonstrated the feasibility of practical CO_2/O_2 breaker based on the philosophy of SF_6 breakers' design. For example, Figure 11 shows the comparison of breakdown electrical field in the arcing gap between the "new" and "APT (after pre-conditioning test)" conditions in capacitive current switching tests. The breaker should be designed so that breakdown does not occur even after multiple large current interruptions, called pre-conditioning. In design phase, significant dielectric performance drop in the arcing gap due to degradation of contact surface and generation of by-product should be properly taken into account. As shown in Figure 11, reduction of dielectric strength due to pre-conditioning was approx. -15% in CO_2/O_2, which was quite similar to the number of SF_6 design experience [14].

The largest technical challenge with CO_2/O_2 natural-origin gas mixtures is obviously similar footprint (equipment size) to SF_6 due to inherent lower dielectric, switching and cooling performance than SF_6. However, replaceable footprint should be potentially manageable by design improvements and innovations, such as elevated filling pressure, special dielectric coatings, novel concepts of a gas interrupter and so forth, as shown in Table 4.



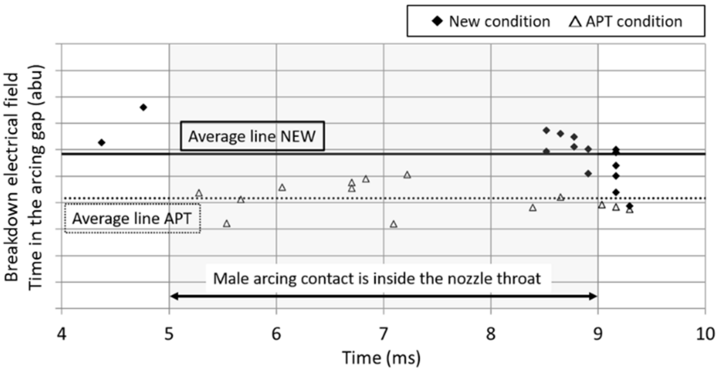
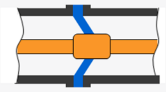
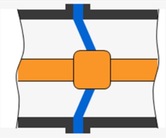
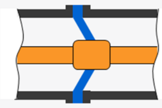
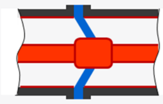
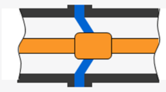


Figure 10 (Left): 168 kV CO_2/O_2 circuit breaker (prototype) in high-power testing.

Figure 11 (Right): Comparison of breakdown electrical field in the arcing gap between the "New" and the "APT (after pre-conditioning test)" conditions in capacitive current switching tests.

Table 4: Tank size reduction of a single-phase bus bar with elevated pressures and special dielectric coatings.

Gas	SF_6	CO_2	CO_2/O_2	CO_2/O_2	CO_2/O_2
Pressure	0.4 MPa-g	0.8 MPa-g	0.8 MPa-g	0.8 MPa-g	1.4 MPa-g
Others	-	-	-	Special dielectric coating	-
Tank diameter	**100%**	**159%**	**122%**	**113%**	**91%**
Sketch					

5 Conclusions

According to the comprehensive survey, practical natural-origin gases (NOG) for high-voltage switchgear applications are N_2, CO_2, O_2 and their mixtures, e.g. synthetic air (N_2/O_2) and CO_2/O_2. It should be noted here that this application is rather a CCUS (Carbon dioxide Capture, Utilization and Storage) and does never generate brand-new CO_2 on the earth. CO_2 is much better than N_2 in terms of switching performance, thus, when considering a gas interrupter (in other words, when not using a vacuum interrupter), CO_2 should be the best candidate of the main gas of mixtures. The addition of O_2 proves many benefits not only from the viewpoint of performance, but also the viewpoints of safety gas handling and lifetime aspects. CO_2/O_2 natural-origin gas mixtures offer excellent aspects in terms of condensation temperature, long-term stability, gas handling, gas availability, potential environmental and regulatory risks. In particular, as a result of large numbers of full-scale tests performed in the168 kV prototype development, an optimized ratio of 70% CO_2 and 30% O_2 represents a well-balanced feasible solution that shows no inherent drawbacks that cannot be overcome by design.

Technical challenges with CO_2/O_2 natural-origin gas mixtures obviously come from inherent lower dielectric, switching and cooling performance than SF_6. However, replaceable footprint (equipment size) should be potentially manageable by design improvements and innovations, such as elevated filling pressure, special dielectric coatings, novel concepts of a gas interrupter and so forth.

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