Pressure Rise in Electrical Installations due to Internal Arcing in CO₂ as Insulating Gas

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Received: February 18, 2015 / Accepted: April 08, 2015 / Published: June 30, 2015.

Abstract: Internal arcs cause a rapid increase in pressure in electrical installations. The type of insulation gas has influence on pressure development. Typically SF₆ is used incompact metal-clad switchgear, however, it has a high global warming potential. Because of this, the replacement of SF₆ by alternative gases such as CO₂ is under discussion. The pressure developments in a closed vessel filled with air, SF₆ and CO₂ are measured and compared. During internal arcing in gas-insulated switchgear, overpressure causes a rupture of a burst plate and hot gas escapes into the surrounding room mixing with air. In order to predict the pressure development in electrical installations reliably, the portion of energy causing pressure rise, arc voltage as well as reliable gas data i.e., thermodynamic and transport properties, must be known in a wide range of pressure and temperature. These data are up to now not available for CO₂/air mixtures. The thermodynamic properties are directly calculated from the number densities, internal partition functions and enthalpies of formation. The transport coefficients are deduced using the Chapman-Enskog method. Comparing measured and calculated pressure developments in a test arrangement demonstrates the quality of the calculation approach.

Key words: Pressure calculations, internal arcing, carbon dioxide.

1. Introduction

Apart from air, SF₆ (sulphur hexafluoride) is the most important insulating gas in metal-clad switchgear in the medium voltage range. Its exceptional dielectric properties allow compact switchgear design. The drawback of SF₆ is its high global warming potential. That is why it is important to reduce the amount of SF₆ in use or to find suitable alternative insulating gases [1]. One of the gases under discussion is CO₂ (carbon dioxide) [2-4].

During internal arcing in electrical installations, the pressure relief device of the gas-insulated compartment opens in general. Hot gas escapes from this compartment and flows into the switchgear room. During this process, the gas density in the

compartment decreases on one hand and on the other hand the exhausted hot gas entering the switchgear room mixes with ambient air causing pressure rise in the room.

In this contribution, the pressure rise in CO₂ due to fault arcs are investigated experimentally and compared with which in air as well as in SF₆. Apart from this, quantities that are necessary for reliable calculations of the pressure development in switchgear rooms, the density dependent thermal transfer coefficient (the portions of electric energy, which results in pressure rise, or k_p -factor) and the arc voltage are determined for these gases. As the gas data of CO₂/air mixtures, which are necessary to calculate the pressure development in switchgear rooms equipped with CO₂ insulated switchgear, have not been available, they are computed in a wide temperature, pressure and CO₂ concentration range.

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2. Determination of Input Data for Pressure Calculation

2.1 Test Setup and Measurement Results

Measurements have been performed in a closed test vessel (70 L; electrode distance 10 cm; Cu electrodes) filled with different insulating gases. The energy source, is a resonant circuit ($L = 314 \mu\text{H}$, $C = 36 \text{ mF}$, charging voltage 4 kV, stored energy nearly 300 kJ).

Arc bending is reduced by the magnetic field of the cage-like arrangement of return conductors. During the tests arc voltage, current and pressure have been measured. A typical current and voltage profile is provided in Fig. 1. The corresponding pressure developments in the test vessel are presented in Fig. 2. Due to the discharge of the condenser bank C the current peak decreases over time. The numbers of half cycles varies with filling pressure and with the type of insulating gas. The arc voltage is nearly constant during the half cycles. The filling pressure has been varied between 25 kPa and 200 kPa.

Due to the smaller heat capacity of air compared with CO₂ and SF₆ in the temperature range up to about 3,000 K (compare Fig. 3) the pressure peak in air is the highest. Inversely, the maximum pressure in the switchgear room (e.g., of a substation) will be expected to occur for SF₆ insulated switchgear. This results from the higher energy density of the heated SF₆ entering the switchgear room. The pressure decay after arc extinction in Fig. 3 is due to heat conduction.

2.2 Energy Transfer Coefficient k_p

The k_p -factor has been determined depending on gas density by varying the filling pressure in the test vessel and adapting calculated pressure developments to measured ones. The calculations are performed using Eq. (1):

$$\Delta p = \frac{\kappa - 1}{V} \cdot k_p \cdot P_{elec} \cdot \Delta t \quad (1)$$

where, κ is the ratio of specific heat capacities; V is the vessel volume and P_{elec} is the electric power [5].

Fig. 1 Current and arc voltage development for a test in CO₂ (filling pressure of the vessel: 100 kPa).

Fig. 2 Pressure development in the test vessel (filling pressure: 100 kPa; arc energy: 180-200 kJ) for different insulating gases.

Fig. 3 Calculated values of the specific heat at constant pressure over temperature for SF₆, CO₂ and air at a pressure of 100 kPa.

The results are provided in Fig. 4, where k_p varies with the filling pressure of the vessel or gas density. For air and CO₂ as insulating gases, it decreases with declining density, while it rises for SF₆. The decrease of k_p for air and CO₂ is attributed to a change in the energy balance at high temperatures. In this case, energy portions, which do not contribute to thermal energy (pressure rise) like radiation, become more important. In SF₆, the particle multiplication by dissociation might be of importance. In the higher range of gas density (filling pressure), the variation of k_p is smaller.

If an arc is ignited in a switchgear compartment with pressure relief opening, the gas density in the enclosure changes over time and by this the k_p -value. This causes a reduction in pressure increase in air and CO₂ within the switchgear room compared with a free burning arc in the room [6].

2.3 Arc Voltage

The arc voltage is a further quantity, which is needed for pressure calculation. It depends on several parameters. One of them is the type of gas. In Fig. 5, measurement values are shown depending on the filling pressure of the test vessel. The arc voltage rises nearly linearly with gas density (filling pressure). This is understandable if one has in mind that with

Fig. 4 k_p -factor depending on filling pressure (gas density) for different insulating gases.

Fig. 5 Measured arc voltages in the test vessel for different filling pressures (10 cm gap distance, arc energy between 180 kJ and 200 kJ) and insulating gases.

increasing particle density more particles are present in the inter-electrode spacing, which must be ionised. Due to the low ionization, potential of sulphur atoms in the arc (and a stabilized arc by the cage of return conductors), the arc voltage in SF₆ is lower than in the other gases. The arc voltages in air and CO₂ do not differ considerably in this arrangement.

3. Thermodynamic and Transport Properties of CO₂/Air Mixtures

3.1 Calculation Methods

To obtain reliable pressure values, thermodynamic and transport properties are needed. Plasma compositions are obtained from the mass action law and from the chemical base concept described in Ref. [7]. Assuming local thermodynamic equilibrium, the calculations were performed for pressures between 0.1 MPa and 10 MPa, temperatures from 300 K to 30,000 K, and several CO₂/air mixture ratios. Thirty-seven molecular species are considered (C₂, C₂⁺, C₂⁻, O₂, O₂⁺, O₂⁻, N₂, N₂⁺, NO, NO⁺, CO, CO⁺, CN, CN⁺, CN⁻, C₃, C₃⁻, CO₂, CO₂⁻, CNN, NCN, C₂N, C₂O, NO₂, NO₂⁻, N₂O, N₂O⁺, O₃, N₃, CNO, C₂N₂, C₄, C₃O₂, NO₃, N₂O₃, N₂O₄, N₂O₅), 14 atomic species (C, O, N, C⁻, C⁺, C²⁺, C³⁺, O⁻, O⁺, O²⁺, O³⁺, N⁻, N⁺, N²⁺, N³⁺) and electrons. For the calculation of the internal

partition functions used in the calculation of the plasma's compositions, the data for atomic species and the spectroscopic constants for the molecular species can be found in Refs. [8-12].

The (mass) density and the enthalpy are directly deduced from the particle densities, their internal partition functions and their enthalpies of formation (starting at 300 K). The specific heat capacity at constant pressure, essential to determine the pressure, has been obtained by the numerical derivative of enthalpy. The transport coefficients (viscosity, electrical and thermal conductivities) were obtained using the Chapman-Enskog method based on the Boltzmann integro-differential equation. These properties are governed by elastic collisions between all the species, which are represented by effective functions called "collision integrals". More details to calculate these functions and to determine the transport coefficients can be found in Ref. [1]. For collisions in pure air and CO₂ plasmas, the collision integrals provided in Refs. [1, 13] have been used. For the mixtures between CO₂ and air, the collisions between carbon and nitrogen species are treated using the Lennard-Jones potentials for neutral-neutral interactions, polarisation potentials for neutral-ion interactions and screened Coulomb potential for charged-charged particles. The associated parameters are taken from Ref. [1].

3.2 Influence of Mixing Ratio

In Figs. 6 and 7, the specific heat at constant pressure and the thermal conductivity for different CO₂/air mixtures at 100 kPa depending on temperature are given. It is observed that, these quantities depend in a similar way changing the mixture ratio. The peaks of the specific heat and of the thermal conductivity, which represent several dissociation or ionization processes, appear at nearly the same temperatures (dissociation of CO₂ and O₂ at approximately 3,500 K, dissociation of CO and N₂ close to 7,000 K, ionization of C, O and N close to 15,000 K).

Fig. 6 Specific heat C_p over temperature for several CO₂/air mixtures (in mole fractions) at 100 kPa.

Fig. 7 Thermal conductivity over temperature for several CO₂/air mixtures (in mole fractions) at 100 kPa.

Concerning the further properties depending on temperature (not presented here), it is worth noting that:

- At low temperatures, the electrical conductivity strongly increases with decreasing air concentration;
- The maximum of the viscosity increases with air concentration and the maximum is slightly shifted to lower temperatures.

These behaviours have already been observed and discussed in previous works [1].

3.3 Validity Using Mixing Rules

Due to the large pressure range (100 kPa-10 MPa), the numerous temperature values (300-30,000 K with 100 K steps) and several gas mixtures, databanks have

to be used in numerical modelling in general. A solution to easily calculate the gas properties could be to apply mixing rules, which allow their estimation using the properties of pure gases. These rules, already studied e.g., in Ref. [14], lead to the following conclusions:

- Van Yun's law can be used to estimate the viscosity;
- Linear laws (with mass or mole fractions) can be used to estimate the electrical conductivity, especially for mixtures without metallic vapors;
- Linear laws (with mass or mole fractions) can be used for the specific heat and the thermal conductivity at certain conditions. The accuracy is acceptable for atomic gases, but it decreases for molecular gases either due to dissociation and ionization reactions, or due to new species created by the mixture of the gases (with SF₆ as insulating gas mixing rules should not be applied [5]).

In case of 50%CO₂/50% air mixture (mole fractions) at 100 kPa, the specific heat and the thermal conductivity are shown in Figs. 8 and 9 obtained according to an "exact" computation and calculations using the mixing rules "linear interpolations" of the mass or the mole fractions, and Wilke's rule [15].

These results show that, the linear interpolation using mass fraction is better than the others to describe the thermal conductivity with decreasing accuracy at high temperatures (Wilke's rule is not acceptable in this case). This interpolation gives also the best results for the specific heat at constant pressure for which the third peak is very well described compared to the thermal conductivity. This good agreement is mainly due to the dissociation and the ionization reactions, which occur at approximately the same temperatures.

3.4 Influence of Pressure

The pressure influence on the properties has been studied as well. The results of the specific heat C_p and the thermal conductivity for a 50%CO₂/50% air mixture (in mole fractions) are presented in Figs. 10

Fig. 8 Calculated thermal conductivity over temperature of a 50%CO₂/50% air mixture (mole fraction) at 100 kPa considering particle interactions and chemical reactions (exact), linear interpolations with mass (mass linear) and mole fractions (mole linear) and the approach of Wilke (Wilke).

Fig. 9 Calculated specific heat at constant pressure C_p over temperature of a 50%CO₂/50% air mixture (in mole fractions) at 100 kPa for different approaches (see caption).

Fig. 10 Calculated specific heat C_p over temperature for a 50%CO₂/50% air mixture (in mole fractions) for different pressures.

Fig. 11 Calculated thermal conductivity over temperature for a 50%CO₂/50% air mixture (in mole fractions) for different pressures.

and 11. The analysis of these two properties leads to several comments:

- The specific heat and the thermal conductivity have similar behaviors varying pressure (presence of the two first peaks at the same temperatures);
- The peaks of the thermal conductivity and of the specific heat C_p are attenuated and shifted to higher temperatures. The shift of the maxima is due to Le Chatelier's principle, which delays dissociation and ionization reactions. The consequence is also a decrease of the peak amplitudes.

For the other properties, one can say that, the maximum of viscosity increases with pressure and is shifted to higher temperatures [1]. The electrical conductivity decreases at low temperature and increases at high temperature because ionization is delayed when pressure rises [1].

From these results, one can conclude that, the variation of the specific heat and the thermal conductivity with pressure is not linear due to dissociation and ionisation reactions. These reactions happen at higher temperatures with rising pressure.

4. Application Example

With the data derived in the preceding sections, the pressure calculations have been performed and compared with measurements in a test arrangement (Fig. 12). It consists of a quad-flange with a volume of

93 L (arc room), a connecting tube of 83 L and a relief room of 840 L. The arc room filled with CO₂ with a pressure of 170 kPa (absolute) is separated from the connecting tube by a rupture disk. The connecting tube and the relief room are filled with ambient air.

The pressure calculations are performed with a tool, which is based on the ideal gas model and the first law of thermodynamics (improved standard calculation method [5]). This tool allows the determination of spatial averaged pressure developments within rooms, which are connected by pressure relief devices even for air as well as gas insulated switchgear.

In Fig. 13, measured and calculated pressure developments in the arc as well as in the relief room are shown of a test with current and voltage shapes similar to those in Fig. 2. After arc ignition, the pressure rises in the arc room. At the response pressure of the rupture disk (240 kPa gauge), the disk opens, CO₂ flows into the relief room and mixes with air. The pressure drops down to 30 kPa (gauge) in the closed system consisting

Fig. 12 Sketch of the test arrangement.

Fig. 13 Calculated and measured pressure developments in the arc and relief room.

of the arc and relief room together with the connecting tube. After about 55 ms pressure, balance between arc and relief room is reached.

From these results follows that reliable pressure calculations with the determined CO₂ data and the calculation approach are possible.

5. Conclusions

The pressure rise in electrical installations due to fault arcs depends on the insulation gas. For the gases air and SF₆, the pressure behaviour is well investigated. This is not true for the alternative insulating gas CO₂. In the gas vessel of the switchgear, where an arc might appear, the overpressure is lowest if SF₆ is used as filling gas and highest for air. For CO₂, it is in between. Because of this (among others), the design of CO₂ insulated switchgear has to be re-considered with respect to internal arcing.

As arc tests are not possible in the planning phase of new installations, reliable pressure calculations are needed. To perform such calculations input data must be available. These are mainly the energy transfer coefficient depending on gas density, arc voltage (or power development) for pressure predictions and reliable pressure and temperature dependent gas data, especially the thermodynamic and transport properties. During the exhaust from heated CO₂ from the gas vessel (arc room) into the relief room (switchgear room), pressure, temperature and the CO₂ concentration continuously change, i.e., the gas data of the CO₂/air mixtures depending on these parameters must be available during numerous iteration processes necessary to solve the equation system for pressure determination. From the analysis of the data, follows that linear interpolations of the gas properties of pure CO₂ and air facilitate the determination of the properties of CO₂/air mixtures.

Furthermore, the thermal transfer coefficient and arc voltage must be known and in general have to be determined experimentally. For the test arrangement under investigation these values are provided.

Acknowledgments

Gerhard Johannes Pietsch and Sebastian Wetzeler gratefully acknowledge the financial support of the German Federal Ministry of Economics and Technology through the AiF project No. 17255N.

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