INFLUENCE OF INSULATING GAS ON PRESSURE RISE IN ELECTRICAL INSTALLATIONS DUE TO INTERNAL ARCS

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ABSTRACT

Internal arcs cause a rapid increase in pressure in electrical installations. The type of insulation gas has influence on pressure rise. Typically SF_6 is used in compact metal-clad switchgear. This gas has a high global warming potential. Because of this the replacement of SF_6 by alternative gases such as CO_2 is under discussion. The pressure developments in a closed vessel filled with CO_2, SF_6 and air are measured and compared. During internal arcing in gas-insulated switchgear the overpressure causes a rupture of a burst plate and heated gas escapes into the surrounding room mixing with air. The portions of electric energy causing overpressure are therefore determined depending on gas density. To perform pressure calculations, reliable gas data and arc voltages are necessary. The arc voltages in the test vessel have been measured. CO_2/air gas data are provided in a wide range of pressure and temperature. The thermodynamic properties are directly calculated from the number densities and from the internal partition functions. The transport coefficients are deduced using the Chapman-Enskog method.

1. INTRODUCTION

Apart from air sulphur hexafluoride (SF_6) is the most important insulating gas in metal-clad switchgear in the medium and high voltage range. Its exceptional dielectric properties allow compact switchgear design. The drawback of SF_6 is its high global warming potential. That is why it is important to reduce the amount of SF_6 in use or to find suitable alternative insulating gases. One of the gases under discussion is carbon dioxide (CO_2).

During internal arcing a pressure relief device of the gas-insulated compartment opens. Hot gases escape from this compartment and flow 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 cold gas causing pressure rise.

In this contribution the pressure rise in CO_2 due to internal arcs is investigated experimentally and compared with those in air as well as in SF_6. Apart from this, quantities that are necessary for reliable calculations of the pressure development in switchgear rooms, the density dependent thermal transfer coefficient (k_p-factor; the portions of electric energy, which results in pressure rise) and the arc voltage are determined for these gases. As the gas data of CO_2/air mixtures, which are necessary to calculate the pressure development in switchgear rooms equipped with CO_2 insulated switchgear, have not been available, they are computed in a wide temperature and pressure range.

2. EXPERIMENTAL RESULTS

Test setup

Measurements have been performed in a closed test vessel (70 L; electrode distance 10 cm; Cu electrodes) filled with different insulating gases. Fig. 1 shows the energy source, which is a LC resonant circuit (L = 314 µH, C = 36 mF, charging voltage 4 kV, stored energy nearly 300 kJ). Arc bending is reduced by the magnetic field of a cage-like arrangement of return conductors.

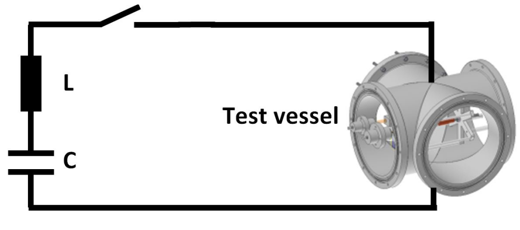

Fig. 1 Sketch of the test circuit

During the tests arc voltage, current and pressure have been measured. A typical current and voltage profile is provided in Fig. 2 and the corresponding pressure developments in the test vessel are presented in Fig. 3. Due to the discharge of the condenser bank C the current peak decreases over time. The number 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 altered between 25 and 200 kPa.

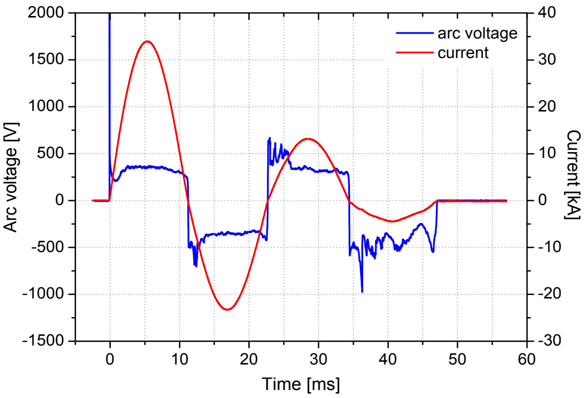

Fig. 2 Current and arc voltage development for a test in CO_2 (filling pressure of the vessel 100 kPa)

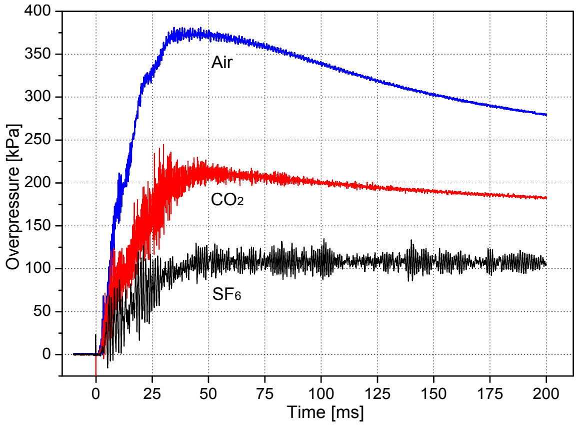

Fig. 3 Pressure development in the test vessel (filling pressure 100 kPa, arc energy 180 to 200 kJ) for different insulating gases

Due to the smaller heat capacity of air compared with CO_2 and SF_6 in the present temperature range the pressure peak in air is the highest. Inversely, the maximum pressure in the switchgear room will be expected to occur for SF_6 insulated switchgear. This results from the higher energy density of the heated SF_6 entering the switchgear room. The pressure decay after arc extinction is due to heat conduction.

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 with the equation

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

where κ is the ratio of specific heat capacities, V the vessel volume and P_{elec} the electric power [1].

The results are provided in Fig. 4, where k_p varies with gas density. For air and CO_2 as insulating gases it decreases with declining density, while it rises for SF_6. The decrease of k_p for air and CO_2 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 SF_6 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.

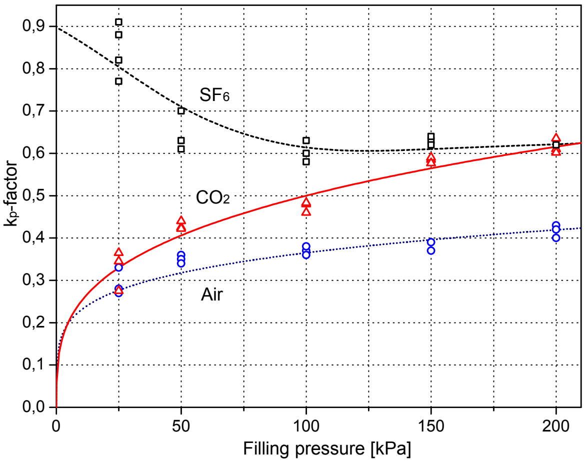

Fig. 4 k_p-factor depending on filling pressure (gas density)

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 CO_2 within the switchgear building compared with a free burning arc in the building (enclosure effect).

Fig. 5 shows the calculated maximum pressure increase in the test setup depending on energy input. The calculations were performed for the same boundary conditions as for the corresponding measurements (symbols). Pressure and temperature dependent gas data have been used as well as the k_p-values given in Fig. 4. The deviation of the measurement points from the calculated curve for CO_2 at 100 kPa results from the fitted k_p-curve taken from Fig. 4. Due to the lower heat capacity of air compared with SF_6 and CO_2, the maximum pressure rise in SF_6 and CO_2

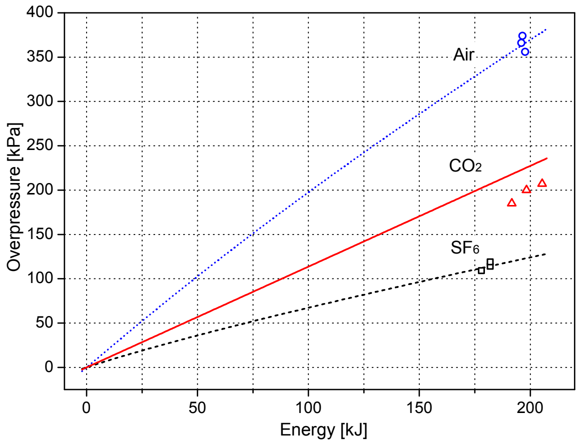

Fig. 5 Calculated and measured pressure increase in the test vessel depending on electrical energy for 100 kPa filling pressure

is about 66 % and 40 % lower than in air at the same boundary conditions.

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. 6 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 increasing particle density more particles are present in the inter-electrode spacing, which must be ionised. Due to the low ionisation potential of sulphur atoms in the arc (and a stabilized arc by the cage of return conductors) the arc voltage in SF_6 is lower than in the other gases. The arc voltages in air and CO_2 do not differ considerably in this arrangement.

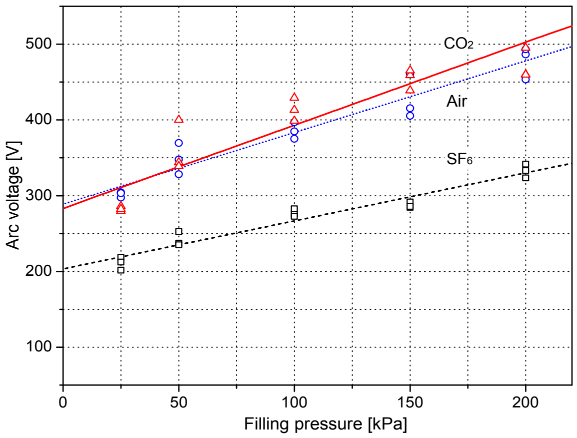

Fig. 6 Measured arc voltages in the test vessel for different filling pressures (10 cm gap distance, arc energy between 180 and 200 kJ)

3. TRANSPORT PROPERTIES OF CO_2/AIR MIXTURES

To obtain reliable pressure values, thermodynamic and transport properties are needed. Plasma compositions were obtained from the mass action law and from the chemical base concept described by Godin and Trepanier [2]. Assuming the Local Thermodynamic Equilibrium, the calculations were done for pressures between 0.1 and 10 MPa, temperatures from 300 K to 30 kK, and several mixtures (step of 10 % mole fraction from pure CO_2 to pure air). 37 molecular species are considered (C_2, C_2^+, C_2^-, O_2, O_2^+, O_2^-, N_2, N_2^+, NO, NO^+, CO, CO^+, CN, CN^+, CN^-, C_3, C_3^-, CO_2, CO_2^-, CNN, NCN, C_2N, C_2O, NO_2, NO_2^-, N_2O, N_2O^+, O_3, N_3, CNO, C_2N_2, C_4, C_3O_2, NO_3, N_2O_3, N_2O_4, N_2O_5), 14 atomic species (C, O, N, C^-, C^+, C^{2+}, C^{3+}, O^-, O^+, O^{2+}, O^{3+}, N^+, N^{2+}, N^{3+}) and electrons.

The mass density and the enthalpy were directly deduced from the number densities, energies and standard states. The specific heat capacity at constant pressure, essential to determine the pressure, was 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 through effective functions called “collision integrals”. More details can be found in [3] to calculate these functions and determine the transport coefficients. For collisions in pure plasmas (air and CO_2), we used the same collision integrals than those in [3, 4]. The collision between carbon and nitrogen species were treated using the Lennard-Jones potentials for neutral-neutral interactions, polarisation potentials for neutral-ion interactions and screened Coulombian potential for charged-charged particles. The associated parameters are given in [3].

It is observed that transport properties are influenced in different ways when air concentration rises in the plasma: the peaks of the thermal conductivity are influenced in terms of amplitude but not really in terms of position; the maximum of the viscosity increases and is slightly shifted to lower temperatures; the electrical conductivity strongly increases at low temperatures.

The thermal conductivity is shown in Fig. 7 for CO_2/air mixtures at 0.1 MPa. The behaviour is similar to the specific heat capacity and presents several peaks corresponding to the dissociation or ionisation phenomena (dissociation of CO_2 and O_2 at approximately 3.5 kK, dissociation of CO and O_2 close to 7 kK, ionisation of C, O and N close to 15 kK).

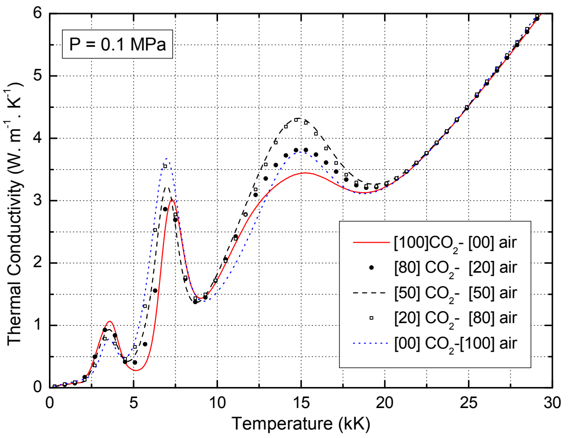

Fig. 7 Thermal conductivity of CO_2/air mixtures for different mole fractions at 0.1 MPa

The pressure influence on the properties have been studied as well: the peaks of the thermal conductivity are attenuated and shifted to higher temperatures and its values are higher at high temperatures; the maximum of viscosity increases and is shifted to higher temperatures; the electrical conductivity decreases at low temperature and increases at high temperature because ionisation is delayed when pressure increases. An example is given in Fig. 8 for the thermal conductivity of pure CO_2.

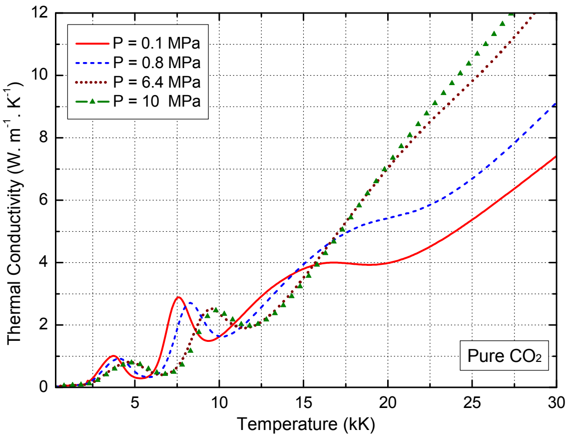

Fig. 8 Thermal conductivity of pure CO_2, influence of pressure

4. CONCLUSIONS

In order to use alternative insulating gases in electrical installations, the design of the installation has to be reconsidered with respect to internal arcing among others. In this connection pressure rise is of importance. In the switchgear compartment, where an arc might appear, the overpressure is lowest if SF_6 is used as filling gas and highest for air. For CO_2 it is in between. This is mainly due to the corresponding heat capacities.

As arc tests are not possible in the planning phase of new installations, reliable pressure calculations must be performed. This is only possible, if pressure and temperature gas data are available. The data for CO_2/air were determined from the plasma compositions and assuming Local Thermodynamic Equilibrium. According to the Chapman-Enskog method, intermediate functions called “collision integrals” were calculated to estimate the transport coefficients: viscosity, electrical conductivity and thermal conductivity. The results show that the presence of air in CO_2 strongly modifies the electrical conductivity and the viscosity altogether and therefore, slightly influences the peaks of the thermal conductivity. Moreover, they highlight the fact that the pressure also modifies these properties, more particularly the viscosity and the thermal conductivity.

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.

ACKNOWLEDGEMENT

G. J. P. and S. W. gratefully acknowledge the financial support of the German Federal Ministry of Economics and Technology through the AiF project No. 17255N.

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