ON THE DESCRIPTION OF THE THERMAL TRANSFER COEFFICIENT $k_p$ OF THE POWER BALANCE OF FAULT ARCS

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Abstract. In order to determine the pressure rise due to internal arcs in electrical installations, the portion of energy heating the surrounding gas must be known. This portion, the thermal transfer coefficient, well known in literature as $k_p$-factor, is adopted here. Within this contribution a calculation method for $k_p$ will be presented. It is modelled taking into account the melting and evaporation of electrode and wall material as well as chemical reactions with the surrounding gas. The calculation results for closed arc compartments show that e.g. the kind of insulating gas and of electrode material, the size of the test vessel as well as the gas density influence the thermal transfer coefficient considerably.

1 Introduction

If an internal arc in an electrical installation occurs, it may endanger the maintenance personnel and seriously damage the electrical equipment and even the building of the installation. One of the main effects of internal arcs is the pressure stress on mechanical parts of the installation and on the walls of the building.

In order to determine the pressure rise, the portion of energy heating the surrounding gas must be known. For modelling the energy transfer from the arc to the surrounding gas it has been assumed that the fraction $P_p$ of the electric arc power $P_e$ heats the surrounding gas leading to the pressure rise $\Delta p$. The thermal transfer coefficient $k_p$ can be expressed as:

$$k_p = \frac{P_p}{P_e} = \frac{Vdp}{(\kappa - 1)P_e dt} \quad (1)$$

where $V$ and $\kappa$ are the volume of the gas space under consideration and the adiabatic coefficient of the insulation gas, respectively [1,2,3].

To simulate the pressure rise in the surroundings of fault arcs several calculation methods have been developed in the past [2,3]. In these approaches the thermal transfer coefficient $k_p$ has to be determined experimentally measuring the pressure development in a closed vessel and applying equation (1). That is why the application of its value is limited to the certain circumstances and special boundary conditions of the experiment. Calculating $k_p$ will enlarge the possibility to determine overpressure in a reliable way considerably.
2 Theoretical model

2.1 Energy transport

If an internal arc occurs, the arc energy is delivered to its surroundings via different interaction mechanisms. The energy input into the plasma by Joule heating is balanced by several energy exchange processes like heat conduction, radiation transport and convection. At the boundary of the arc channel radiation and plasma jets mainly cause the heating of the surrounding gas and by that pressure rise. Furthermore, metal vapour from the arc roots together with chemical reactions play an important role in the energy transfer from the arc to the insulation gas. If openings of the arc compartments (e. g. pressure relief flaps in switchboards) are present, the gas expansion must be considered additionally.

Based on these considerations a power balance of the arc can be formulated dividing each power portion by the electric power $P_e$ (neglecting the interaction of the arc with its solid environment):

\[ 1 = k_p + k_{\text{cond}} + k_{\text{rad}} + k_{\text{conv}} + k_{\text{exp}} \]  

(2)

where $k_{\text{cond}}$, $k_{\text{rad}}$, $k_{\text{conv}}$, and $k_{\text{exp}}$ are coefficients representing the power of heat conduction, radiation, convection and gas expansion, respectively.

2.2 The concept of "relative purity"

In order to understand the following, it is of advantage to introduce the term "relative purity" of the gas status. If a gas surrounding an arc is not contaminated by impurities (from the electrodes or the interaction of the arc with walls), it will be named "pure". If at a given electric energy of the arc the gas density is high enough so that the particle concentration of the impurities generated by the arc is negligible, it will be named "relative pure". The thermal transfer coefficient at "relative purity" $k_{pp}$ can be determined from equation (1) together with pressure measurements in closed vessels at high gas densities. Its value has found to be constant and independent of the gas model to a large extent [3].

Due to the heat transfer at the roots of the arc, conductors, metallic bars or walls will melt and evaporate to a certain amount. Metallic vapours can even dominate the gas composition. They can react with the insulation gas, e. g. in exothermic chemical reactions. By these reactions chemical energy will be fed into the thermodynamic system additionally. In this case chemical reactions and material evaporation have to be considered in the thermodynamic system and will influence the pressure development (Fig. 1). The thermal transfer coefficient $k_p$ at high gas temperatures, with gas impurities and in arrangements with relief openings is characterised by the mutual dependency of the power coefficients:

\[ k_p = k_{p0} + k_{m+v} - k_{\text{chem}} \]  

(3)

where $k_{m+v}$ and $k_{\text{chem}}$ are the coefficients corresponding to the melting and evaporation process and to chemical reactions, respectively.
2.3 Governing equations

The additional particles resulting from metal vapour (e.g. Al or Cu) lead to a change in the gas density:

\[
\frac{d\rho_i}{dt} = k_{m+v}' I(t), \quad i = 0
\]  \hspace{2cm} (4)

where \( I(t) \) and \( k_{m+v}' \) are the current and the specific mass loss per charge unit, which is proportional to the \( k_{m+v}' \)-coefficient.

Due to chemical reactions, the additional gas density follows from the contributions of the reaction rates:

\[
\frac{d\rho_i}{dt} = \mu_i n_i R_i \quad i = 1, 2, \ldots, m
\]  \hspace{2cm} (5)

where \( \mu_i, n_i, R_i \) and \( \dot{m} \) are the relative molar weight of the gas species, the overall stoichiometric coefficient, reaction rate and kind of species. It is reasonable to suppose that the rates of chemical reactions are faster than that of metal vaporisation.

In order to consider the other power portions of equation (2) a mathematical model has been developed. The physical approach is based on the conservation equations of mass (continuity equation), momentum (Navier-Stokes equations) and energy (power balance).

Continuity equation:

\[
\frac{\partial}{\partial t} (\rho y_i) + \nabla (\rho \bar{u} y_i - (\Gamma_i + \frac{\mu_r}{\sigma_i}) \nabla y_i) = \sum_{i=0}^{m} \frac{d\rho_i}{dt}
\]  \hspace{2cm} (6)

where \( y_i, \bar{u}, \Gamma_i, \mu_r \), and \( \sigma_i \) are the species, velocity, diffusion coefficient, turbulent viscosity and the turbulent Prandtl number.
Momentum equation:

\[
\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla(\rho \vec{u} \otimes \vec{u}) = \sum_{i=0}^{m} \frac{\partial(\rho_i \vec{u}_i)}{\partial t} + \nabla \sigma \tag{7}
\]

with \( \sigma \) the stress tensor.

Energy conservation equation:

\[
\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{u} H) - \nabla(\lambda \nabla T) = \frac{\partial p}{\partial t} + \frac{k_{pb} P_e}{V} + \sum_{i=0}^{m} \frac{\partial(\rho_i H_i)}{\partial t} \tag{8}
\]

with \( \lambda \) the thermal conductivity of the gas.

### 3 Simulation results

In order to estimate the influence of some relevant parameters on over-pressure like the kind of electrode material, insulation gas, the volume of the test vessel and gas density, it is assumed that a fault arc with an electric power of 100 kW during 80 ms occurs inside a closed vessel of different volume \( (V_s = 0.07 \text{ m}^3 \text{ and } V_l = 0.14 \text{ m}^3) \) at conditions given in Table 1:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>insulation gas</td>
<td>air or SF(_6)</td>
</tr>
<tr>
<td>initial gas pressure</td>
<td>0.01 ~ 0.3 MPa</td>
</tr>
<tr>
<td>initial temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>short circuit current</td>
<td>2.0 ~ 10.0 kA</td>
</tr>
<tr>
<td>duration of short circuit</td>
<td>0.08 s</td>
</tr>
<tr>
<td>thermal transfer coefficient ( k_p )</td>
<td>0.60</td>
</tr>
<tr>
<td>conductor material</td>
<td>Al or Cu</td>
</tr>
<tr>
<td>volume</td>
<td>0.07 or 0.14 m(^3)</td>
</tr>
<tr>
<td>density of electrical energy</td>
<td>0.4 ~ 0.8 MJ/m(^3)</td>
</tr>
</tbody>
</table>

Table 1: Test conditions.

Metal evaporation as well as the following set of chemical reactions between the insulation gas air and the electrode material aluminium and copper, respectively, have been considered:

\[
4 \cdot Al + 3 \cdot O_2 = 2 \cdot Al_2O_3 + P_{chem} \tag{9}
\]
\[
Cu + 0.5 \cdot O_2 = CuO + P_{chem} \tag{10}
\]
\[
Cu + O_2 = CuO_2 + P_{chem} \tag{11}
\]

In SF\(_6\) metal evaporation has been taken into account only.

Experimental results are available for these conditions [3]. The calculation and measurement results of the thermal transfer coefficient for closed test vessels are presented in Fig. 2 to 5 as function of the initial pressure (gas density) of the test vessel. A rather good agreement between both can be recognised.

From equation (1) it is known that the thermal transfer coefficient \( k_p \) depends (apart from the electric energy) on the adiabatic coefficient \( \kappa \) and on the pressure rise \( \Delta p \). In order to compare the \( k_p \)-value following from measurement and calculation without the influence of
the value of $\kappa$ (which depends on temperature only) the $\kappa$-values belonging to ambient temperature (300 K) have been used in all cases.

In Fig. 2 and 3 the results belong to the insulation gas air and the electrode material aluminium and copper, respectively. For an initial air pressure above 0.1 MPa (corresponding to an air density of 1.2 kg/m$^3$), the $k_p$-value is in the range of 0.75 to 0.80. For gas densities below 0.1 MPa (1.2 kg/m$^3$), the $k_p$-value decreases to around 0.45 with falling pressure.

**Fig. 2:** Calculated and measured $k_p$-values for Al-conductors (electrodes) in air depending on gas density (initial pressure of the test vessel).

**Fig. 3:** Calculated and measured $k_p$-values for Cu-conductors (electrodes) in air depending on gas density (initial pressure of the test vessel).
In Fig. 4 and 5 the thermal transfer coefficient is given for SF₆ and the electrode materials aluminium and copper. With (initial) gas pressures above 0.1 MPa (corresponding to a gas density of 6.1 kg/m³) the calculated $k_p$-value is nearly constant about 0.60 to 0.65 in both vessels. Below 0.1 MPa (6.1 kg/m³), the $k_p$-value rises up to about 1.0 and 1.2 depending on the size of the vessel in the case of aluminium electrodes. In the case of copper electrodes the $k_p$-value is nearly unchanged.

Fig. 4: Calculated and measured $k_p$-values for Al-conductors (electrodes) in SF₆ depending on gas density (initial pressure of the test vessel).

Fig. 5: Calculated and measured $k_p$-values for Cu-conductors (electrodes) in SF₆ depending on gas density (initial pressure of the test vessel).
Based on the evaporation rate of copper given in [1], the portion of copper vapour in SF₆ at an (initial) gas pressure of 0.3 MPa (18.3 kg/m³) and the further conditions given in Table 1 is 0.068 % and 0.035 % in the test vessel of 0.07 m³ and 0.14 m³, respectively. Calculating the overpressure in the test vessels a mean temperature of 333 to 354 K of the insulation gas has been found. That is why the gas is "relative pure" in this case, i. e. the influences of the metal vapour and chemical reactions are negligible.

On the other hand in the case of aluminium electrodes, the portion of metal vapour at an (initial) air pressure of 0.01 MPa (0.012 kg/m³) is 19.6 %. The calculated temperature at this condition has found to be 3813 K (at a power density of 0.8 MJ/m³). In such a case the gas status is far from "relative purity".

4 Discussion and conclusions

If "relative purity" of a certain insulation gas is given at high gas densities (e. g. for SF₆), the measured value of \( k_{p0}(\text{SF}_6) \) can be used to determine those of other insulation gases X, \( k_{p0}(X) \). At "relative purity" the pressure rise caused by a fault arc depends only on the internal energy of the gas, which is proportional to the specific heat of the gas at constant volume \( c_v \). That is why

\[
k_{p0}(X) = c_v(X)/c_v(\text{SF}_6) \cdot k_{p0}(\text{SF}_6).
\]

Comparing the shape of the \( k_p \)-curve over gas density for air and SF₆ some differences are obvious. While in air the \( k_p \)-factor decreases with falling gas densities, it increases in the case of SF₆ (or is about constant). This results from the rising importance of the consumption of O₂- and Al-particles in chemical reactions in the case of air as insulation gas. In the case of SF₆ such a consumption is not present, on the contrary, with aluminium electrodes a strong evaporation of the metal happens, which increases the pressure considerably. The evaporation of copper is less important.

The results in Fig. 2 and 3 (for air) are similar. The \( k_p \)-values differ only a bit in the low density range depending on the size of the vessel. Regarding initial pressures below 0.1 MPa (1.2 kg/m³) in the larger vessel, the total number of O₂-particles is so large that chemical reactions will not consume all of them. However, in the smaller vessel the chemical reactions consume nearly all O₂-particles so that the thermal transfer coefficients \( k_p \) will be smaller (Fig. 2 and 3).

If chemical reactions are absent (e. g. because of a lack of O₂-particles) the gas production may follow from a boosting evaporation of electrode and/or wall material, which in tendency may rise the \( k_p \)-value.

With smaller gas density the insulation gas is heated to a higher temperature by the same energy. In this case the percentage of generated gas by e. g. evaporation is enlarged rising the pressure on one hand. Chemical reactions on the other hand, which yield solid reaction products, lead to a gas consumption and by that to a decrease of the pressure. In general the number density of additional generated or consumed particles plays a decisive role.

This effect is important in electrical installations with pressure relief openings as well. During the gas stream through the relief flaps, the gas density decreases. In order to take the density decrease into account for pressure calculations, the particular value of the \( k_p \)-factor has to be used, which corresponds to the actual gas density and which has been determined in the closed vessel. (It is expected that the exact shape of the \( k_p \)-curve depends on the amount of energy released in the gas volume at least at low gas densities.)
Comparing the $k_p$-values at high gas densities of air and of SF$_6$, the values of air are enlarged in tendency. This follows from the differences in the specific heat at constant volume of both gases (at ambient temperature), which is larger for air.

With the presented approach it has been demonstrated that it is possible to calculate the thermal transfer coefficient $k_p$ in dependence of the gas density in a reliable way. The knowledge of $k_p$ at different boundary conditions e. g. concerning the insulation gas, electrode material, volume of the arc chamber, short circuit power, enables over-pressure calculations in closed vessels and installations with relief openings. For this purpose the melting and evaporation of electrodes and of walls as well as chemical reactions between the insulation gas and the generated vapour have to be considered.

5 References

