DETERMINATION OF THE THERMAL TRANSFER KOEFFICIENT $k_p$ OF THE ENERGY BALANCE OF FAULT ARCS IN ELECTRICAL INSTALLATIONS

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ABSTRACT

In order to determine the pressure rise due to internal arcs in electrical installations, the portion of the electrical energy causing overpressure must be known. This portion, the thermal transfer coefficient, in literature known as $k_p$-factor, depends on the kind of insulation gas, its density, on the size of the arc compartment and on the type of electrode material.

In this contribution a theoretical approach to determine $k_p$ is presented. It is based on the solution of the fundamental hydrodynamic conservation equations taking into account melting and evaporation of metals as well as chemical reactions with the insulation gas. This approach has proved to be a reliable tool to calculate 3D pressure developments.

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 buildings.

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 gas it has been assumed that the fraction $W_e$ of the electric arc energy $W_e$ heats the surrounding gas leading to the pressure rise $\Delta p$. The thermal transfer coefficient $k_p$ can be expressed as:

$$k_p = \frac{W_p}{W_e} = \frac{Vdp}{(k-1)P_e dt} \quad (1)$$

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

In the past several calculation methods have been developed to simulate the pressure rise in the surroundings of fault arcs [2, 3]. In these approaches the thermal transfer coefficient $k_p$ was determined experimentally in closed vessels applying equation (1) most often for relative large volumes. That is why the application of $k_p$-values is limited to the special boundary conditions of the experiment and the assumptions of the gas model used in equation (1). In general the $k_p$-factor from literature cannot be used especially in small arc chambers where electrode material vaporisation is important.

There is another reason for the necessity to calculate the thermal transfer coefficient $k_p$. In some cases stations are included in existing buildings without the possibility to determine the pressure stress by fault arc tests on site.

ENERGY BALANCE OF FAULT ARCS

If an internal arc occurs, the arc energy is released in the surroundings by different interaction mechanisms (Fig. 1). The energy input into the arc by Joule heating is balanced by several energy exchange processes like heat conduction, radiation transport and convection. At the boundary of the arc channel mainly its expansion and plasma jets cause the heating of the surrounding gas and by that pressure rise. Furthermore, metal vapour from the arc roots together with chemical reactions of the vapour play an important role in the energy transfer from the arc to the insulation gas.

Based on these considerations an energy balance of the arc can be formulated dividing each energy portion by the electric energy $W_e$:

![Power Balance Diagram](image)

**Fig. 1.** Simplified power balance of a fault arc in an electrical installation.
\[ 1 = k_p + k_{\text{cond}} + k_{\text{rad}} + k_{\text{conv}} \quad (2) \]

where \( k_{\text{cond}} \), \( k_{\text{rad}} \), and \( k_{\text{conv}} \) are coefficients representing the energy of heat conduction, radiation and convection, respectively. The effects of melting, vaporisation and chemical reactions are included in \( k_p \).

THE CONCEPT OF "RELATIVE PURITY"

In order to understand the following, it is advantageous to introduce the term "relative purity" of a gas. If a gas is not contaminated by impurities from e.g. vaporisation, it will be named "pure". If the gas density is rather high so that the particle concentration of impurities generated by the arc is negligible at a given electric energy input, it will be named "relative pure". The thermal transfer coefficient at "relative purity" \( k_{p0} \) can be determined from equation (1) by pressure measurements in closed vessels at high gas densities (which means simultaneously low average gas temperatures). \( k_{p0} \) has been found to be constant at varying gas density and independent of the gas model to a large extent [3].

If "relative purity" of a certain insulation gas is given the measured value of \( k_{p0} \) (at high gas densities) can be used to determine that of other insulation gases \( X \).

For SF\(_6\) the value of \( k_{p0} \) has been found to be

\[ k_{p0}(\text{SF}_6) = 0.6 \quad (3) \]

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 values of the specific heat at constant volume \( c_v \). That is why

\[ k_{p0}(X) = c_v(X)/c_v(\text{SF}_6) \cdot k_{p0}(\text{SF}_6) \quad (4) \]

If the condition "relative purity" is not fulfilled, a considerable portion of electrode material will be vaporised. Metallic vapours can even dominate the gas composition. The vaporised particles will directly influence the pressure stress on one hand. On the other hand the vapour may react with the insulation gas in endothermic or exothermic reactions influencing the energy balance and in addition the particle density (if e.g. chemical reactions lead to powders, extracting particles from the gas volume). The thermal transfer coefficient \( k_p \) with gas impurities is characterised by the mutual dependency of the energy transfer coefficients \( k_{p0} \), \( k_{\text{m+}} \) and \( k_{\text{chem}} \)

\[ k_p = k_{p0} + k_{\text{m+}} + k_{\text{chem}} \quad (5) \]

THEORETICAL MODEL

In order to determine the thermal transfer coefficient \( k_p \), \( k_{\text{m+}} \) and \( k_{\text{chem}} \) must be known.

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

\[ \frac{d\rho_j}{dt} = k_{\text{m+}} f(t) \quad (6) \]

where \( f \) and \( k_{\text{m+}} \) are the current and the specific mass loss per charge unit, which is proportional to the \( k_{\text{m+}} \)-coefficient.

If metal (copper, aluminium, iron) is evaporated in air the following reactions have to be considered:

\[
\begin{align*}
2 \cdot \text{Cu} + \text{O}_2 & = 2 \cdot \text{CuO} + 310 \text{ kJ/mol} \quad (7.1) \\
\text{Cu} + \text{O}_2 & = \text{CuO}_2 + 168 \text{ kJ/mol} \quad (7.2) \\
4 \cdot \text{Al} + 3 \cdot \text{O}_2 & = 2 \cdot \text{Al}_2\text{O}_3 + 3350 \text{ kJ/mol} \quad (7.3) \\
3 \cdot \text{Fe} + 2 \cdot \text{O}_2 & = \text{Fe}_3\text{O}_4 + 1118 \text{ kJ/mol} \quad (7.4) \\
4 \cdot \text{Fe} + 3 \cdot \text{O}_2 & = 2 \cdot \text{Fe}_2\text{O}_3 + 1644 \text{ kJ/mol} \quad (7.5)
\end{align*}
\]

Due to chemical reactions, a gas density change results from the contributions of the reaction rates:

\[ \frac{d\rho_j}{dt} = M_j n_j R_j \quad (8) \]

where \( M_j \), \( n_j \) and \( R_j \) are the molar weight of the \( j \)-th component of the reaction \( j \), the overall stoichiometric coefficient and the reaction rate, respectively. It is reasonable to assume that the reaction rates are faster than that of metal vaporisation.

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

Continuity equation:

\[
\frac{\partial}{\partial t} (\rho \psi) + \nabla (\rho \psi \vec{u}) = -(\Gamma_i + \mu_i) \nabla \psi = \sum \frac{d\rho_i}{dt} \quad (9)
\]

where \( \psi \) is the portion of a compound which consists of \( i \)-components (species), \( \vec{u} \), \( \nabla \), \( \mu \), and \( \Gamma_i \) are the velocity, diffusion coefficient, turbulent viscosity and the turbulent Prandt number, respectively.

Momentum equation:

\[
\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla (\rho \vec{u} \vec{u}) = -\nabla p + \mu \vec{\nabla} \vec{u} + \left( \zeta + \frac{H}{3} \right) \nabla (\nabla \vec{u}) \quad (10)
\]
with \( \zeta \) the bulk and \( \mu \) the dynamic viscosity.

Energy conservation equation:

\[
\frac{\partial}{\partial t}(\rho H) + \nabla (\rho \mathbf{u} H) - \nabla (\lambda \nabla T) = \frac{\partial p}{\partial t} + \frac{1}{\rho} \nabla \cdot \mathbf{F} + \sum_i \frac{\partial (\rho_i H_i)}{\partial t}
\]

(11)

with \( \lambda \) the thermal conductivity and \( H \) the specific enthalpy of the gas.

RESULTS

With the model described above the thermal transfer coefficient \( k_p \) has been determined for air, SF\(_6\) and different electrode materials. The results for copper and air as insulating gas together with those from measurements [3] are presented in Fig. 2 as function of gas density (or the initial gas pressure) of the closed test vessel. A satisfactory agreement can be recognised.

For an initial air pressure above 0.1 MPa (corresponding to an air density of more than 1.2 kg/m\(^3\)), the \( k_p \)-value is in the range of 0.65 to 0.75. For gas densities below 0.1 MPa (1.2 kg/m\(^3\)), the \( k_p \)-value decreases to around 0.45 with diminishing pressures.

As an example for overpressure determination a fault in a compact MV station with severe metal evaporation is considered (Fig. 3), for which measurement results are available. The relevant volumes and cross sections of relief openings are given below:

![Diagram](image)

**Fig. 2:** Calculated (lines) and measured (dots) \( k_p \)-values depending on air density (copper electrodes) for two volumes of the test vessel.

**Fig. 3:** Side, front and top view of the compact MV station under consideration.

The short-circuit was initiated in one of three cable compartments, which are connected with one another by openings O2-2. The fault developed to a three-phase one of 16 kA current and 1.0 s duration. The run of the resulting power curve is presented in Fig. 4.

During the course of the fault about 1 kg of the housing of the switch compartment (iron sheet) was evaporated as well as about 100 g copper from the electrodes.

In Fig. 5 and 6 the calculated and measured pressure curves are depicted in the middle of the cable compartments R2 and in the middle of the transformer room R3, respectively. The results are in rather good agreement.

The maximum pressure of about 120 and 105 kPa in the middle of R2 and R3 are reached about 20 and 40 ms after arc ignition. The oscillation of the pressure during the first pressure peak in R3 is believed to result from the action of the opening to the environment O3. After this (at \( t = 0.05 \) s) the relief openings cause a strong pressure decay to about 103 kPa in both rooms.
Fig. 4: Measured power slope of a short-circuit of 16 kA during 1 s

After about 200 ms a further (and smaller) increase of the power occurs. It results from the burning-through of the housing of the switch compartment and is connected with heavy iron evaporation. About 90% of the gas in the cable compartment now consists of iron vapour. From this follows an increase in arc voltage and pressure lasting for about 350 ms. After that a constant level of overpressure is reached up to extinction of the fault arcs.

At t = 800 ms a further oscillation of the pressure in measurement as well as calculation is detected, which belongs to an enforced power oscillation during the last 200 ms, which may result from strong arc movements.

CONCLUSIONS

In order to be able to predict overpressures in electrical installations due to internal arcs it is necessary to know the thermal transfer coefficient \( k_p \), the portion of arc energy, which causes overpressure. With its knowledge it is possible to determine overpressures even for severe conditions like in the case of large energy input in small volumes (with heavy metal evaporation) and in cases where experiments cannot be performed.

A method has been developed to calculate the \( k_p \)-factor depending on gas density on the basis of the relevant hydrodynamic conservation equations taking into account metal evaporation, chemical reactions of the vapour with the surrounding gas and the chemical energies of the reactions. This knowledge is important for pressure determinations in electrical installations with pressure relief openings.

It has been proved that calculated and measured \( k_p \)-dependencies on gas density are in satisfactory agreement with one another. Furthermore, it is demonstrated with the example of a short circuit in a compact MV station and heavy metal evaporation that the tool developed is able to calculate overpressure developments with high precision.

REFERENCES

