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Calculation of pressure and temperature in medium-voltage electrical installations due to fault arcs

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Abstract
In order to determine the pressure rise due to arc faults in electrical installations, the portion of energy heating the surrounding gas of fault arcs has to be known. The ratio of the portion of energy to the electric energy, the thermal transfer coefficient, is adopted as the \( k_p \) factor. This paper presents a theoretical approach for the determination of the thermal transfer coefficient and the pressure rise in electrical installations. It is based on the fundamental hydro- and thermodynamic conservation equations and the equation of gas state taking into account melting and evaporation of metals as well as chemical reactions with the surrounding gas. In order to consider the dependence of the arc energy on the gas density, the radiative effect of fault arcs on the energy balance is introduced into the arc model by using the net emission coefficient as a function of gas density, arc temperature and arc radius. The results for a test container show that factors such as the kinds of insulating gases and of electrode materials, the size of test vessels and the gas density considerably influence the thermal transfer coefficient and thus the pressure rise. Furthermore, it is demonstrated, for an example of the arc fault in a compact medium-voltage station with pressure relief openings and a pressure relief channel, that the arc energy and the arc temperature can be simulated based on the changing gas density.

(Some figures in this article are in colour only in the electronic version)

Nomenclature

\( c_v \) specific heat at constant volume (J kg\(^{-1}\) K\(^{-1}\))
\( E \) electric field strength (V m\(^{-1}\))
\( h \) specific enthalpy (J kg\(^{-1}\))
\( H \) total enthalpy (J)
\( i \) order number
\( I \) effective value of short-circuit current (kA)
\( I_s \) spectral intensity (W m\(^{-2}\) sr\(^{-1}\) Hz\(^{-1}\))
\( j \) order number
\( J_1 \) Bessel function of the first kind of order 1
\( k_{\text{chem}} \) transfer coefficient of chemical reaction
\( k_{\text{cond}} \) transfer coefficient of conduction
\( k_{\text{conv}} \) transfer coefficient of convection
\( k_{\text{m+v}} \) transfer coefficient of melting and evaporation
\( k_p \) thermal transfer coefficient
\( k_Q \) heat transfer coefficient
\( k_{\text{rad}} \) radiation transfer coefficient
\( m \) order of gas mixture; mass (kg)
\( M \) molecular mass (kg mol\(^{-1}\))
\( n \) order of chemical reactions
\( p \) pressure (Pa)
\( Q \) heat (J)
\( r \) chemical reaction rate (mol s\(^{-1}\)); distance (m)
\( R \) radius (m)
\( S \) source term (kg s\(^{-1}\) m\(^{-3}\), kg s\(^{-2}\) m\(^{-2}\), J s\(^{-1}\) m\(^{-3}\))
\( t \) time (s)
\( T \) temperature (K)
1. Introduction

Electrical installations are used to divide the total electric energy into a number of dispersed load points to meet the energy requirement of electric systems and customers. Therefore, the reliability of electrical installations is an important factor for the evaluation of modern electric systems. If an arc fault occurs in an electrical installation, it may seriously damage the electrical equipment and the buildings of the installation, and even endanger the maintenance personnel as well as the reliability of the electric energy supply. The main effects of an arc fault are the pressure stress and the high temperature on the mechanical and electrical parts of the installation, and even endanger the maintenance personnel. In these approaches the pressure rise has been determined, by which the consequences of arc faults can be determined. But the importance of simulation has been increasing steadily since simulations allow access to information that cannot be obtained by measurements. For this reason, the fault arc model and the investigation of the thermal transfer coefficient, as given in this paper, can estimate the reliability of electrical installations and the security of electric power systems.

It is known from some results of experiment that the thermal transfer coefficient $k_p$ depends mainly on several parameters such as the kinds of insulating gases and electrode materials, the size of test vessels and the gas density [5, 6]. However, experimental results from an electrical installation are not easily conferrable to other installations with different device descriptions and structural types. In some cases, electrical equipment and installations are even destroyed and made unusable by fault arcs or electrical stations are included in existing buildings without the possibility of determining the pressure stress via tests on site. Before estimating the thermal transfer coefficient $k_p$, the gas temperature has to be known in order to determine the adiabatic coefficients $\kappa$ according to (1). In those strongly simplified arc models [5], however, the forecasting of arc performance when the arc voltage is assumed as an unchanged variable has yielded a too high arc temperature. On the assumption of homogeneous arc energy [5], the local divergence of gas density in an electrical installation with pressure relief openings causes a non-homogeneous local distribution of gas temperature. Furthermore, some relevant investigations [6–9] actually demonstrate that the arc voltage depends on the initial pressure in electrical installations or the gas density in closed test containers.

Up to now, the arc energy and the pressure rise have been measured, by which the consequences of arc faults can be determined. But the importance of simulation has been increasing steadily since simulations allow access to information that cannot be obtained by measurements. For this reason, the fault arc model and the investigation of the thermal transfer coefficient, as given in this paper, can estimate the reliability of electrical installations and the security of electric power systems.
If a fault arc occurs in an electrical installation, the electric energy of the arc plasma is transferred to its surroundings via different mechanisms of interaction (figure 2). The energy input $W_{arc}$ into the fault arc not only heats the surrounding gas, but also converts into heat conduction $W_{cond}$ and radiation $W_{rad}$ by interactions of the arc column with the electrodes and the walls of the electrical installation as well as the surrounding gas. The conduction and radiation fractions of energy escaping from the fault arc, which are not absorbed by the gas around the fault arc, are absorbed by these electrodes and the walls of the electrical installation. This is due to the fact that the thermal capacity of the electrodes and the walls is much larger than those of the gas existing in the electrical installation, and the time constant of the heat transfer from the electrodes and the walls back to the surrounding gas is significantly larger than the duration of a typical arc fault, so that the retroactive effect of the heating electrodes and the walls on the surrounding gas can be negligible. Through the electrodes and the walls of the electrical installation the heat conduction and the radiation are eventually transferred to the ‘cold’ gas outside the electrical installation, which does not participate in heating the surrounding gas of the fault arc. So the energy balance can be written as:

$$W_{arc} = Q + W_{cond} + W_{rad}. \quad (2)$$

The heat energy $Q$ is transferred into the surrounding gas inside the electrical installation. In the considered system, the heat energy $Q$ involves the internal energy $U$, the convection $W_{conv}$, the melting and evaporation $W_{m+v}$ as well as the chemical reactions $W_{chem}$:

$$Q = U + W_{conv} - W_{m+v} \pm W_{chem}. \quad (3)$$

If the openings of the electrical installation (e.g. the pressure relief flaps in switchboards) are present, the convective exchanges $W_{conv}$ of heat and gas mass cause a change in the internal heat of the surrounding gas and, therefore, the thermal transfer coefficient also. Furthermore, metals evaporated from the arc root points together with chemical reactions play an important role in the energy transfer from the fault arc to the surrounding gas. The metal evaporation enhances the gas quantities and further increases the thermal transfer coefficient. The energy necessary for melting and evaporation is to be considered in the energy balance [4, 10]. Due to chemical reactions between the evaporated materials and the surrounding gas, the oxidation of the evaporated metals with air results in a decrease in particles in the surrounding gas around the fault arc. The heat $W_{chem}$ of chemical reactions makes a considerable contribution to the energy balance of the fault arc [4, 11].

Based on the above discussions, the energy balance of fault arc can be formulated, dividing each energy portion by the electric energy $W_{arc}$:

$$k_p = (1 - k_{cond} - k_{rad}) - k_{conv} + k_{m+v} \pm k_{chem}, \quad (4)$$

where $k_{cond}$, $k_{rad}$, $k_{conv}$, $k_{m+v}$ and $k_{chem}$ are the coefficients representing the energy of conduction, radiation, convection, melting and evaporation as well as chemical reaction, respectively (with the symbols ‘+’ for an endothermic reaction and ‘−’ for an exothermic reaction).

The internal energy ($k_p$) is composed of those energy portions contributing to the surrounding gas ($1 - k_{cond} - k_{rad}$), convection ($k_{conv}$) by pressure relief flaps, as well as metallic vapos ($k_{m+v}$) and their chemical reactions ($k_{chem}$). According to the experimental results from [4–6, 8, 12, 13] for both closed and open containers or electrical installations, the radiation coefficient $k_{rad}$ remains almost unaffected and the conduction coefficient $k_{cond}$ is relatively small; thus its value is negligible. For these reasons, the heat transfer coefficient $k_Q$ can be assumed to be constant:

$$k_Q = 1 - k_{cond} - k_{rad}, \quad (5)$$

and, thus, (4) can be simplified to

$$k_p = k_Q - k_{conv} + k_{m+v} \pm k_{chem}. \quad (6)$$

3. Concept of the ‘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 the fault arc in a closed container is not contaminated by impurities from the electrodes or the interaction of the fault arc with the walls of the container, it is named ‘pure’. If, at a given electric energy of the fault arc, the gas density in a closed container is high enough so that the particle concentration of the impurities generated by the fault arc is negligible, it is named ‘relatively pure’.

From (6) we can find that the heat transfer coefficient $k_Q$ is just the thermal transfer coefficient $k_p$ at ‘relatively pure’ conditions because other coefficients have no contribution to (6). The heat transfer coefficient $k_Q$ can be determined from (1) by the measurement of pressure in a closed container at high gas densities, which means a fixed substance constituent and a comparatively low average temperature of the surrounding gas. The heat transfer coefficient $k_Q$ of an insulating gas, whose value depends on the kind of insulating gas and is independent of the gas model to a large extent, is found to be constant at high gas densities. The $k_Q$ value of SF$_6$ as the insulating gas.
is found to be \([4–6, 13]\)

\[
k_Q(SF_6) = 0.60. \tag{7}
\]

For a ‘relatively pure’ insulating gas, the thermal transfer coefficient \(k_p\), i.e. the heat transfer coefficient \(k_Q\), depends on the internal energy of gas, which is proportional to the specific heat \(c_v\) at constant volume of an insulating gas \([11]\) if the change in temperature of the surrounding gas is low and the temperature of the surrounding gas is accepted as the ambient temperature. Thus, the \(k_Q\) values of another insulating gas \(X\) can easily be determined by \(k_Q(SF_6)\):

\[
k_Q = c_v(X)/c_v(SF_6) \cdot k_Q(SF_6). \tag{8}
\]

Due to the heat transfer at the arc roots, the metal electrodes or walls of the test container may melt and evaporate to a certain extent. In the case of low gas density metallic vapours can even dominate the gas compositions and the condition of ‘relative purity’ will not be fulfilled. The vaporized particles will directly influence the pressure stress. Furthermore, the vapours may react with the surrounding gas in endothermic or exothermic reactions, influencing the energy balance of the fault arc and the density of the surrounding gas (if, for example, chemical reactions lead to powders, extracting particles from the surrounding gas). In this case, material evaporation and chemical reactions have to be considered in the thermodynamic system because they will influence the pressure development.

4. Evaporation and chemical reactions

During a fault arc, additional particles resulting from metal vapours (e.g. copper, aluminium or iron) result in a change in the density of the surrounding gas in an electrical installation \([4]\):

\[
V \frac{d \rho_i}{dt} = \alpha_i I, \quad i = 1, 2, \ldots, m, \tag{9}
\]

where \(t\) is time, \(I\) the effective value of the short-circuit current, \(i\) the order number, \(m\) the order of the gas mixture, \(\rho_i\) the density for \(i = 1, 2, \ldots, m\), corresponding to various components, and \(\alpha_i\) the specific mass loss per charge \(I \cdot t\) of the \(i\)th component, which is proportional to the \(k_{m+v}\) coefficient \([4, 10]\).

The energy \(W_{m+v}\) for melting and evaporation is to be considered in the energy balance, i.e. \([10]\)

\[
\text{Me (solid state)} + W_{m+v} = \text{Me (gaseous state)}, \tag{10.0}
\]

where Me stands for different metals, e.g. Al, Cu and Fe.

If metals (Al, Cu or Fe) evaporate to air, the following chemical reactions have to be considered:

\[
\begin{align*}
2\text{Cu} + \text{O}_2 & = 2\text{CuO} + W_{\text{chem}}, \tag{10.1} \\
\text{Cu} + \text{O}_2 & = \text{CuO}_2 + W_{\text{chem}}, \tag{10.2} \\
4\text{Al} + 3\text{O}_2 & = 2\text{Al}_2\text{O}_3 + W_{\text{chem}}, \tag{10.3} \\
3\text{Fe} + 2\text{O}_2 & = \text{Fe}_3\text{O}_4 + W_{\text{chem}}, \tag{10.4} \\
4\text{Fe} + 3\text{O}_2 & = 2\text{Fe}_2\text{O}_3 + W_{\text{chem}}. \tag{10.5}
\end{align*}
\]

Due to chemical reactions, the reaction rates \([11]\) contribute to a change in the gas density

\[
\frac{d \rho_i}{dr} = M_i v_{i,j} r_j, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n, \tag{11}
\]

where \(j\) is the order number, \(n\) the order of chemical reactions, \(v_{i,j}\) the stoichiometric coefficient of the \(i\)th component in the \(j\)th chemical reaction, \(M_i\) the molecular mass for \(i = 1, 2, \ldots, m\), corresponding to various components and \(r_j\) the chemical reaction rate for \(j = 1, 2, \ldots, n\), corresponding to various chemical reactions.

The energy \(W_{m+v}\) for melting and evaporation and the heat \(W_{\text{chem}}\) of the chemical reaction can be represented by the specific enthalpy \(h_i\) of the generated or consumed gases \(\rho_i\) for \(i = 1, 2, \ldots, m\) \([11]\):

\[
W_{m+v}, W_{\text{chem}} = \sum_{i=1}^{m} \rho_i h_i V. \tag{12}
\]

All processes of melting and evaporating as well as chemical reactions can be described mathematically. The thermodynamic data, e.g. enthalpy, are required for the stoichiometric circumstances of each product and reaction participating in melting and evaporation as well as chemical reactions so that the converted mass and the released energy of reaction materials are involved in the models.

5. Radiation effect of the fault arc

As a fault arc possessing high temperature emits radiative energy from it into its surrounding gas in a test container, the interaction of the fault arc with the surrounding gas has a considerable influence on the energy balance of the fault arc. According to the experimental results of \([4, 6]\), the optical radiation that is emitted by a fault arc includes the spectral range from the ultraviolet region to the infrared region > 200–1000 nm. It is recognized that the arc energy is radiated mostly in the ultraviolet range. In order to determine the optical boundary between the arc volume and its surrounding gas, a local distribution of radiation must be quantified in the considered system. The ratio of the radiation energy \(W_{\text{rad}}(r)\) at a distance \(r > 2\) mm of the arc centre to that at infinity \(r \rightarrow \infty\) results analytically from

\[
\frac{W_{\text{rad}}(r)\big|_{r \rightarrow \infty}}{W_{\text{rad}}(r)} = \left(\int_0^r \frac{I_{\lambda}(r)}{I_{\lambda0}} \cdot 2\pi r dr \over \int_0^\infty \frac{I_{\lambda}(r)}{I_{\lambda0}} \cdot 2\pi r dr\right) \approx 1 \tag{13}
\]

according to the relationship between the spectral intensity \(I_{\lambda}(r)\) at a distance \(r\) of the arc centre to the maximum value \(I_{\lambda0}\) at the arc centre \(r = 0\) \([12]\):

\[
\frac{I_{\lambda}(r)}{I_{\lambda0}} = \left[2 \cdot \frac{J_1(2\pi r / \lambda \sin \theta)}{2\pi r / \lambda \sin \theta}\right]^2 \sin \theta \geq 0.61 \frac{\lambda}{r}, \tag{14}
\]
involved in the gas density, the transition probability and the excitation energy which get radiation are to be integrated with the average wavelength, terms of molecular or atomic structures: the characteristics of that radiation is determined by dissociation and ionization in to the difference in energy levels. This is due to the fact inelastic impacts, electrons bring the energy up to higher gas densities, however, it becomes considerable. With arcs, under atmospheric pressure, is of no great concern. At arc radius \( R \), the plasma and the surrounding gas according to the radiation. The part \( k_{\text{rad}} \cdot W_{\text{arc}} \) of an arc energy, passing through the surrounding gas, arrives at the electrodes and walls of the electrical installation while the other part \( (1 - k_{\text{rad}}) \cdot W_{\text{arc}} \) of the arc energy is reabsorbed at the arc boundary and released further into the surrounding gas by convection, thermal conduction and electromagnetic radiation which yield the internal energy \( U \) of the surrounding gas (figure 3).

The results obtained clarify that the radiation from fault arcs, under atmospheric pressure, is of no great concern. At high gas densities, however, it becomes considerable. With inelastic impacts, electrons bring the energy up to higher excitation levels. If accelerated electrons descend once again into lower energy levels, the light quantum is emitted due to the difference in energy levels. This is due to the fact that radiation is determined by dissociation and ionization in terms of molecular or atomic structures: the characteristics of radiation are to be integrated with the average wavelength, the transition probability and the excitation energy which get involved in the gas density \( \rho \), the arc temperature \( T \) and the arc radius \( R \), i.e.

\[
W_{\text{rad}} = k_{\text{rad}} \cdot W_{\text{arc}} = 4 \pi \varepsilon_{N}(T, \rho, R) = k_{\text{rad}} \cdot \sigma E^{2},
\]

(15)

where \( \varepsilon_{N} \), \( \sigma \) and \( E \) are the net emission coefficient, electrical conductivity and the electric field strength, respectively.

Although the radiation \( W_{\text{rad}} \) becomes smaller with the decrease in gas density, the radiation transfer coefficient \( k_{\text{rad}} \) remains nearly unchanged because the arc energy \( W_{\text{arc}} \) decreases along with the declining gas density. Several investigations [6–9, 13, 14] also give the pressure dependence of arc properties, principally through the density dependence of gas pressure, which is closely proportional to the gas density. Therefore, (15) may be rewritten as

\[
W_{\text{arc}} = \frac{4 \pi \varepsilon_{N0}(T, R)}{1 - k_{Q}} \bigg( \frac{\rho}{\rho_{0}} \bigg)^{\beta},
\]

(16)

where \( \rho_{0} \) is the gas density at atmospheric pressure of 0.1 MPa, \( \varepsilon_{N0} \) is the net emission coefficient in accordance with the gas density \( \rho_{0} \) and \( \beta \) is the empirical power value for air or SF_{6}.

In agreement with [8], the assumption is made that, for high current arcs, the temperature profile tends to be isothermal rather than parabolic, i.e. the arc plasma is an isothermal cylinder with the arc radius \( R \). Ohm’s law gives a simple expression for the arc radius \( R \) by the electrical conductivity \( \sigma \) and the effective value \( I \) of the total fault arc current

\[
R = \sqrt{\frac{(1 - k_{Q}) I^{2}}{4 \pi \varepsilon_{N0}(T, R) \sigma(T) \rho_{0}^{\beta}}},
\]

(17)

The expression involves the material function \( \varepsilon_{N0}(T), \sigma(T) \) of the arc plasma, so that the prediction can be made for any arc medium, e.g. air or SF_{6}, whose material functions are acknowledged by [15–18]. This constitutes a simple analysis, based on rather crude simplifications of the energy transfer between the fault arc and the surrounding gas: its advantage is to show that the basic phenomena may be expressed and explained.

6. Governing equations

With the consideration of the thermal transfer coefficient and other transfer coefficients [4], the relevant mathematical model [19] is developed, for which the equation of state and the conservation equations (i.e. continuity, momentum and energy equations) based on hydro- and thermodynamics are applied. The conservation equation can be described in a general form:

\[
\frac{\partial (\rho \Phi)}{\partial t} + \nabla \cdot (\rho \vec{u} \Phi) - \nabla \cdot (\Gamma \nabla \Phi) = S.
\]

(18)

As an independent alternative variable \( \Phi \), the specific enthalpy \( h \), the velocity vector \( \vec{u} \) and the value one are applied for the energy balance, the impulse balance and the mass balance, respectively. \( S \) and \( \Gamma \) are the source term and the transport coefficient for conduction, diffusion and viscosity.

For gas mixtures the functions of material (e.g. gas density, specific heat) [20–22] are determined by the linear priority of components in accordance with the mass fraction \( \chi_{i} \) of the species \( i \) out of \( m \) gas compositions:

\[
\Phi = \sum_{i=1}^{m} \chi_{i} \Phi_{i}.
\]

(19)

With the special expression of melting and evaporation as well as chemical reactions [9–11], the general physical description of the source term in (18) is changed into a mathematical mass, impulse or energy equation:

\[
S = \begin{cases} 
\frac{k_{Q}}{V} \frac{dW_{\text{arc}}}{dr} + \sum_{i=1}^{m} \frac{\partial (\rho_{i} \Phi_{i})}{\partial t} & \text{for } \Phi = h, \\
\sum_{i=1}^{m} \frac{\partial (\rho_{i} \Phi_{i})}{\partial t} & \text{otherwise.}
\end{cases}
\]

(20)

In the conservation (18), the density, velocity or enthalpy gradient \( \partial (\rho \Phi)/\partial t \) from gas compositions, that participate in material melting and evaporation as well as chemical reactions described by (9), (10.0)–(10.5), (11) and (12), appears in (20) as the source term, which describes the change in the generated or consumed particles in mass, impulse and energy.
According to thermodynamics [11], the internal energy $U$ can be specified by the enthalpy $H = m \cdot h$ and the pressure $p$:

$$H = U + p \cdot \Delta V.$$  \hfill (21)

Together with other terms such as convection $\nabla (\rho u \Phi)$ and conduction $\nabla (\Gamma \nabla \Phi)$, (18) is in accordance with the energy balance (6) using the transfer coefficients.

In a gas mixture in the local thermodynamic equilibrium the parameters of the gas state can be explicitly determined by pressure and temperature:

$$\rho = \rho(p, T).$$  \hfill (22)

Using (7)–(12), (16)–(21) and the equation of state, the pressure rise, the gas density, the temperature and the flow velocity as well as other hydro- and thermodynamic items in the electrical installation can be calculated with the sole assumption of (7).

### 7. Simulation results

In order to investigate whether the arc energy depends on the gas density, the effective arc voltages of fault arcs have been measured inside a closed test container by changing the initial pressure (figure 4). As the arc voltage for a given short-circuit current is a direct equivalent of the arc energy, it is important to investigate the relationship between the arc voltage and the gas density. The four-flanged container illustrated in figure 4 is used as a single-pole gas-insulated test container. During a flashover, the fault arc is ignited between two electrodes 5 inserted into the test container through covers. By removing the lateral cover of the pressure transmitter 3, the volume of the container can be varied. The test container is connected to a compressor via two connectors 1 and 2. By activating the compressor, it is possible to fill the test container and to set different initial pressures and the corresponding filling densities in such an enclosure. The initial pressure for the experiment is established at 10 or 300 kPa in air and SF$_6$. It may be mentioned that the exponent value $\beta$ is larger for SF$_6$ than for air. This variation tendency for the exponent value $\beta$ may be subject to the fact that, for a given current, the overpressure is remarkably higher in air than in SF$_6$, on the one hand, and the average measured arc voltage, on the other hand, is considerably lower in air than in SF$_6$. Since SF$_6$ dissociates at lower temperatures than air, it is expected that the adiabatic coefficient of SF$_6$ is lower than in air; it means that air converts the internal energy into a mechanical one more efficiently than SF$_6$; the overpressure in air should be higher than in SF$_6$. These two effects are responsible for the exponent value of (16): the exponent value $\beta$ is slightly lower in air than in SF$_6$ and therefore accepted as 0.22 and 0.43 for air and SF$_6$. As mentioned above, the exponent value $\beta$ of (16) characterizes the effect of gas density on the effective arc voltage or the arc energy and constitutes an important parameter for the arc energy in electrical installations.

| Table 1. The exponent values $\beta$ of gas density determined by the arc voltage at different initial pressures of 300/10 kPa for air and SF$_6$ (Distance of electrodes: 200 mm). |
|---|---|---|---|
| Arc voltage (V) at pressure (300/10 kPa) | $\beta$ | Arc voltage (V) at pressure (300/10 kPa) | $\beta$ |
| No | $\beta$ | No | $\beta$ |
| Air | 760/460 | 0.15 | SF$_6$ | 1000/220 | 0.45 |
| 2 | 700/240 | 0.32 | 2 | 920/200 | 0.45 |
| 3 | 600/320 | 0.18 | 3 | 960/260 | 0.38 |
| 4 | 540/240 | 0.24 | 4 | 940/220 | 0.43 |

From a large number of tests, it can be observed that a decrease in pressure leads to a notable decrease in the effective arc voltage. By applying regression analysis to these test results, the exponent values $\beta$ are determined for different insulating gases air and SF$_6$. It may be mentioned that the exponent value $\beta$ is larger for SF$_6$ than for air. This variation tendency for the exponent value $\beta$ may be subject to the fact that, for a given current, the overpressure is remarkably higher in air than in SF$_6$, on the one hand, and the average measured arc voltage, on the other hand, is considerably lower in air than in SF$_6$. Since SF$_6$ dissociates at lower temperatures than air, it is expected that the adiabatic coefficient of SF$_6$ is lower than in air; it means that air converts the internal energy into a mechanical one more efficiently than SF$_6$; the overpressure in air should be higher than in SF$_6$. These two effects are responsible for the exponent value of (16): the exponent value $\beta$ is slightly lower in air than in SF$_6$ and therefore accepted as 0.22 and 0.43 for air and SF$_6$. As mentioned above, the exponent value $\beta$ of (16) characterizes the effect of gas density on the effective arc voltage or the arc energy and constitutes an important parameter for the arc energy in electrical installations.

The density dependence of the effective arc voltage or the arc energy is considered not only by radiation but also by conductivity. The behaviour of the effective arc voltage is reversely proportional to the electrical conductivity $\sigma$, which is associated with the gas density. As known, the electrical conductivity is in accordance with the collision time. At low gas densities, fewer collisions lead to longer times between collisions and therefore higher conductivity. Concerning the arc voltage, the dissociation of SF$_6$ at lower temperature with respect to air probably makes the electric field of the arc higher by reducing the arc radius.

The influences of some relevant parameters (e.g. electrode material, insulating gas, gas density and the volume of the test vessel) on the pressure rise have to be investigated. In order to do so, a fault arc with an electric power of 100 kW for 80 ms is provided for the experiment, which occurs inside a closed container of different volumes ($V_i = 0.07$ m$^3$ and $V_j = 0.14$ m$^3$) under the conditions given in table 2.

In combination with the boundary conditions given in table 2, the pressure rises are calculated by the knowledge of $k_Q$ in this paper or by the measured $k_p$ values in [5]. On the basis of these results, the thermal transfer coefficient $k_p$ in dependence on the gas temperature can be determined by (1) and shown in figures 5 and 6. The metal evaporation and chemical reactions between the insulating gas air and the...
Table 2. Test Conditions.

<table>
<thead>
<tr>
<th>Insulation gas</th>
<th>Air or SF$_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial gas pressure</td>
<td>0.01–0.3 MPa</td>
</tr>
<tr>
<td>Ambient 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 at ‘relatively pure’ conditions of SF$_6$</td>
<td>0.60</td>
</tr>
<tr>
<td>Electrode 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 electric energy</td>
<td>0.4 to 0.8 MJ m$^{-3}$</td>
</tr>
</tbody>
</table>

Figure 5. $k_p$ values calculated in this work and those derived from [5] for Al and Cu electrodes in air plotted versus the gas density.

Figure 6. $k_p$ values calculated in this work and those derived from [5] for Al and Cu electrodes in SF$_6$ plotted versus the gas density.

It is remarkable that the results of figures 5 and 6 obviously differ from one another below the gas density of 1.21 kg m$^{-3}$. The reason for the deviation is due to the fact that the different temperatures, derived from these two approaches, are applied for the estimation of the adiabatic coefficient. From (1), it is known that the thermal transfer coefficient depends on the pressure rise $\Delta p$ and also on the adiabatic coefficient $\kappa$.

Calculating the arc temperature in this paper, the radiative effect of fault arcs is taken into consideration whereas the profile of temperature is flat in the arc centre. According to radiation, the maximum temperatures in the domains of the fault arc and the surrounding gas are found out to be about 10,000 K and 400 K, respectively. These values are compatible with the experimental results [3, 8]. These results of [5] show an average temperature of 17,500 K of the surrounding gas on the assumption that the arc energy is independent of the gas density.

For example, the curve $k_p$ of ‘air-Cu-Vl’ for the insulating gas air, the electrode material Cu and the larger volume of container, calculated by this paper, slightly rises while the corresponding result of ‘air-Cu-Vl-[5]’ derived from [5] sharply declines, as shown in figure 5. As the insulating gas SF$_6$ has a larger molecular mass and thus a lower temperature than air, a smaller difference in the thermal transfer coefficients between these two methods is found in figure 6.

To compare the $k_p$ values without any influence of different temperatures, instead of comparing the pressure stresses from measurement and calculation, the $\kappa$ values of different insulating gases have to be used at ambient temperature (300 K) for assessment of the thermal transfer coefficient $k_p$. First, the pressure rise $\Delta p$ is experimentally measured due to fault arcs. The measured thermal transfer coefficient can be derived from (1). In the same way the calculated thermal transfer coefficient $k_p$ can be calculated also by (1), after the development of pressure is calculated by using (7)–(12) and (16)–(22). In comparison with the measured and calculated thermal transfer coefficients, the influences of the relevant parameters on the pressure rise can be studied and the approach for the pressure calculation can also be verified. The calculated and measured results of the thermal transfer coefficient $k_p$ for the closed container are presented in figures 7–10 as a function of the gas density (initial pressure). A rather good agreement between both calculated and measured results can be observed.

In figures 7 and 8, the results depict the insulating gas air with the electrode materials aluminium and copper, electrode materials aluminium and copper are considered in (9), (10.0)–(10.5), (11) and (12). When SF$_6$ is used as an insulating gas, only the metal evaporation is taken into account. Considering that the diffusion velocity of metal vopurs is fairly rapid, metal vopurs disperse unorderly in the arc volume and its surrounding gas.

It is remarkable that the results of figures 5 and 6 obviously differ from one another below the gas density of 1.21 kg m$^{-3}$. The reason for the deviation is due to the fact that the different temperatures, derived from these two approaches, are applied for the estimation of the adiabatic coefficient. From (1), it is known that the thermal transfer coefficient depends on the pressure rise $\Delta p$ and also on the adiabatic coefficient $\kappa$.
coefficients $k_p$ (corresponding to a density of 1.2 kg m$^{-3}$) respectively. For the initial pressures of air above 0.1 MPa (corresponding to a density of 1.2 kg m$^{-3}$), the $k_p$ values are in the range 0.60–0.80. For initial pressures below 0.1 MPa (1.2 kg m$^{-3}$), the $k_p$ values decline to about 0.30–0.50 with the falling pressure. In figures 9 and 10, the thermal transfer coefficients $k_p$ are displayed for the insulating gas SF$_6$ and the electrode materials aluminium and copper. With an initial gas pressure above 0.1 MPa (corresponding to a density of 6.1 kg m$^{-3}$), the calculated $k_p$ values are almost constant at about 0.50–0.70 in both volumes of the test container. Below the initial pressure of 0.1 MPa (6.1 kg m$^{-3}$), the $k_p$ values rise up to about 1.0 and 1.2 depending on the volume of container in the case of aluminium electrodes. In the case of copper electrodes, the $k_p$ values remain almost unchanged.

Comparing the shapes of the $k_p$ curves versus the gas density for air and SF$_6$, their differences are obvious, as shown in figures 7–10. While the $k_p$ factors in air decrease with the falling density, they increase or are about constant in SF$_6$. The appearance results from the growing importance of the consumption of O$_2$ and Al particles in chemical reactions if air is used as an insulating gas. In the case of SF$_6$ as an insulating gas, such consumption is not possible. In contrast, strong evaporation of aluminium electrodes occurs in SF$_6$, which considerably increases the pressure. Copper has a relatively smaller amount of evaporation.

At high gas densities, the $k_p$ values are larger in air than in SF$_6$. This consequence results from the difference in the specific heat of an insulating gas at a constant volume, which is higher for air. A similar reason can well explain why, at high gas densities, the resulting $k_p$ values appear slightly larger with aluminium electrodes than with copper electrodes during the evaporation of metal electrodes.

As presented in figures 7 and 8, the $k_p$ values differ from one another in the range of low density, depending on the volume of the container. In the larger volume, the weight of the O$_2$ fraction is 3.26 g. In contrast, it is only 1.63 g in the smaller one. In order to meet the conditions of chemical reactions described by (11) and (12), the evaporated Al or Cu particles of 3.42 or 1.71 g will consume O$_2$ molecules of 3.05 g or 0.58 g, respectively. In the larger volume, O$_2$ molecules are so numerous that they may not be exhausted by chemical reactions. By means of the consumption of O$_2$ particles, the thermal transfer coefficient $k_p$ becomes smaller. However, if chemical reactions are absent because of the lack of O$_2$ molecules in the smaller one, gas products may result from the boosting evaporation of the aluminium electrode material, which may improve the $k_p$ value as presented in figure 7.

Based on the specific mass loss $\alpha$ of metal vapours and the experimental conditions given in table 2, the mass fraction of copper vapours is 0.035% in the container volume of 0.14 m$^3$ at the initial pressure of 0.3 MPa (18.3 kg m$^{-3}$) for SF$_6$. Calculating the overpressure in the test container, the average temperatures of 333 K have been found in the surrounding gas. This is why the surrounding gas of fault arc is indeed ‘relatively pure’ in this case, i.e. the influences of metal vapours and chemical reactions are negligible. On the other hand, in the case of aluminium electrodes the mass fraction of aluminium vapours is 19.6% in both the volumes of the test container. In this case, the gas status is far from ‘relative purity’.

At the low gas density, the surrounding gas is heated to a high temperature by arc energy. In the event, the pressure is quickly raised on the one hand by adding mass fraction and evaporation energy of metal vapours to the surrounding gas. On the other hand, chemical reactions that yield solid
products contribute to the consumption of gases and by that to the moderate pressure rise. In general, the additional generated or consumed particles play a prominent role in determining the development of pressure.

The described calculation method is applied for an example of the fault arc in a medium-voltage compact station with switchgear, cable and transformer compartments as well as pressure relief openings (figure 11). The relevant geometrical conditions are given in table 3. It is expected that the calculation of pressure and temperature depending on the arc energy can reflect the variation of the actual gas density in the compact station.

Before ignition, the initial pressure of 101 kPa and the ambient temperature of 300 K are set in all air-insulated compartments. There is an opening O_1 in the floor at the rear of the switchgear compartment R_1, which guides the gas into the cable compartment R_2 as a buffer volume. After circulation in the cable compartment the gas flows into the transformer compartment R_3 through a rather big opening O_2. Finally the gas finds an escape to the outside through a relief opening O_3 or a relief channel. A short-circuit current of I = 14 kA with an initial phase angle $\varphi = 80^\circ$ is initiated in the switchgear compartment R_1. The fault arc, which burns between the copper electrodes, develops to a three-phase arc fault with a duration of 1.0 s as shown in figure 12. The equipment on test is fitted with pressure sensors. In an environment subjected to numerous disturbances (electromagnetic, thermal and luminous), it is relatively difficult to measure overpressures of just a few millibars. The sensors therefore have to be carefully protected and the signals filtered [2–5, 23, 24].

Therefore, the total arc energy of the fault arcs can be determined by the total fault current. Accompanied by the boundary conditions given in table 3, the pressure rise is calculated and measured in the middle of the cable compartment R_2 as depicted in figure 13 if the relief channel is not considered at first. A rather good agreement between both calculated and measured results can be observed and the calculation approach can also be verified. After arc ignition the pressures tend to increase with the concurrent gradients. Up to 15 ms maximum pressures of about 112 kPa are simultaneously reached. After the first pressure peak, the pressures begin to decline. During the fall in pressure, a small oscillation on the descent curves can be detected which may be due to the impact of an exterior environment on the opening O_3. The maximum deviation of the calculated pressure is found to be below 16% from the measured value.

Sometimes it might be possible to connect the compact station with the outside through a relief channel. In figure 11 the transformer compartment R_3 is supplied with a channel via the opening O_3. The influence of the channel on the pressure and the temperature in the compact station is investigated. With a CFD program it is possible to calculate spatially gas flows at given boundary conditions. In figure 14 the propagation process of a shock wave is investigated intensively in the station with the channel. The gas of the compact station acts as an oscillating system, in which it is excited to a considerable amplitude by compressible gas of the channel. By means of gas oscillation, the pressure progresses in advance. At openings, the pressure wave will be reflected and superposed on the
approaching wave. The period of the oscillation depends on
the frequency of fault arc power, the geometric structure
of the compact station (e.g. diameter of opening and length
of channel) and gas velocity. The decay of oscillation in pressure
is clearly recognized that the inertia of gas mass causes a strong
decay of pressure as much as descending to the initial pressure.

Furthermore, the temperature development is observed
in the middle of the cable compartment. The reasons for the
temperature rise are given by the rapid heating of the arc
volume, by the reabsorption of radiation at the arc boundary
and by the heat transport of the arc plasma into its surrounding
gas. According to the calculated arc energy, the maximum
temperatures in the middle of the switchgear compartment,
the cable compartment and the relief channel are found to be 10 000 K, 500 K and 350 K, respectively. Calculating the
temperature in this paper, the dependence of the arc energy on
the gas density is taken into consideration. For air or SF6, the
net emission coefficient εN in the temperature range 10 000–
20 000 K rises more rapidly than the electrical conductivity σ.

At the arc temperature of $T < 10 000$ K, the net emission coefficient does not increase much due to the fact that the
radiation transfer coefficient is assumed to be approximately
constant [8]. As the energy balance between radiation and
conductivity is in agreement, the arc temperature remains
at around 10 000 K. By experiment the arc temperatures are
determined between 8000 and 12 000 K [3, 8], and therefore
the calculated values of the arc temperature are accessible.
It is concluded that the radiation model is valid for the
determination of the arc temperature in the case of the arc
fault.

8. Conclusions

Based on the accurate arc power and CFD, a new calculation
method is developed in this paper, with which the pressure
rise, the gas temperature, the flow velocity, as well as other
hydro- and thermodynamic items in the case of the arc fault,
can be simulated. By comparison of the calculation results with
available examples, it is shown that the calculation method is
an important tool for the predication of security and reliability
in electrical installations due to arc faults.

In the evolution of an energy balance for the calculation
of the pressure, the term ‘relative purity’ of the gas status is
introduced and the thermal transfer coefficient at ‘relatively
pure’ conditions is measured to be constant for the insulating
gases. Thus the thermal transfer coefficient for any conditions
can be characterized by the thermal transfer coefficient at ‘relatively pure’ conditions together with other transfer
coefficients related to melting and evaporation as well as
chemical reactions. The calculated and measured results show
that the development of pressure and its corresponding thermal
transfer coefficient are dependent on the kinds of insulating gas
and electrode material, the size of the test vessel and the gas
density.

An investigation of radiation around the fault arc reveals
that the arc energy depends on the varying gas density and gas
temperature, which is particularly important for those electrical
installations with pressure relief openings. In consideration
of radiation, the more exact arc energy is introduced into the
energy balance for the estimation of the gas temperature.

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Figure 14. The calculated pressure and temperature in the middle of
the cable compartment R2.


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