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Electric Arc-Contact Interaction in High Current Gasblast Circuit Breakers

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Abstract

Electric arc-contact interaction is studied in high current gas-blast circuit breakers. The aim is to investigate how metal impurities, generated during the high current phase of current interruption, are distributed in the electric arc and to derive simplified relations that can be used in industrial circuit breaker development to estimate the effect of contact erosion.

Impurities in the form of both metal droplets and metal vapour can be ejected from the contact. These impurities are known to affect the ability of circuit breakers to interrupt the current. To study the first, a complete set of equations is proposed to model droplets of molten metal evaporating in a circuit breaker arc. The Initial speed and diameter of the droplets are varied to characterize their behaviour and study the distribution of metal vapour. A relation is derived that can be used in simplified arc models such as integral or two-zone models, to take the effect of droplets into account. It is found that although the influence on usually measured quantities such as pressure and voltage is small, droplets affect velocity and temperature fields in the electric arc significantly and should not be neglected.

To study contact evaporation, a one dimensional model for the near cathode region of electric arcs is applied to define the current, heat and mass transfer mechanisms in a temperature and pressure range of interest in interruption technology. A copper-tungsten cathode is investigated and it is found that evaporation is an important cooling mechanism of the cathode and should not be neglected. The plasma near the cathode is constituted of evaporated contact material in the main part of the investigated pressure-temperature domain.

Descriptors: Electric arc, contact erosion, contact evaporation, near cathode region, metal droplets, metal particles, CFD, computational fluid dynamics, MHD, magnetohydrodynamics.

To Ulrika

Contents

Chapter 1

Introduction

A circuit breaker is an important component in an electric network and its function is to switch off the current in case of a fault or in case a component needs to be disconnected. In closed position, the breaker shall conduct the current with minimum losses. In open position, it must be a good insulator that does not allow any current to flow.

The network can be thought of as a circuit with different components in terms of resistances, inductances and capacitances. The networks considered here have voltage ratings between $72.5kV$ and $800kV$. When the current is switched off, or when a fault occurs, transient oscillations are induced in the network that may be much higher than the supply voltage. To minimize these transients, the breaker must interrupt the alternating current as smooth as possible when it naturally passes zero, i.e. at "current zero". Typical currents that must be interrupted by the breaker lie between a few kA and $100kA$.

Current interruption starts by mechanically separating two contacts. Due to the high current, the gap between the contacts is bridged by a plasma with good electrical conductivity, an arc, so that the current continues to flow. The breaker must remove the conductivity between the contacts in order to interrupt the current. This can be done by cooling the arc, which can reach temperatures close to $20\ 000K$, or removing the hot plasma near current zero.

The properties of the arc strongly depend on the medium in which it is burning. Thus, the medium between the contacts at current zero greatly influences the behaviour of the arc and the ability of the breaker to interrupt the current. Circuit breakers exist with different types of working medium, e.g air, oil, SF_6 and a mixture of SF_6 with N_2 or CF_4. Here, gas blast breakers with SF_6 are considered. Circuit breakers where the contacts are separated in vacuum also exist. The arc is burning in metallic vapours produced at the contacts due to heating by the arc itself.

Figure 1.1 illustrates the working principle of a self blast breaker with pre compression. In closed position (a), the current passes through the main contacts (2). As the contacts are separated (b), the main contacts open first and all

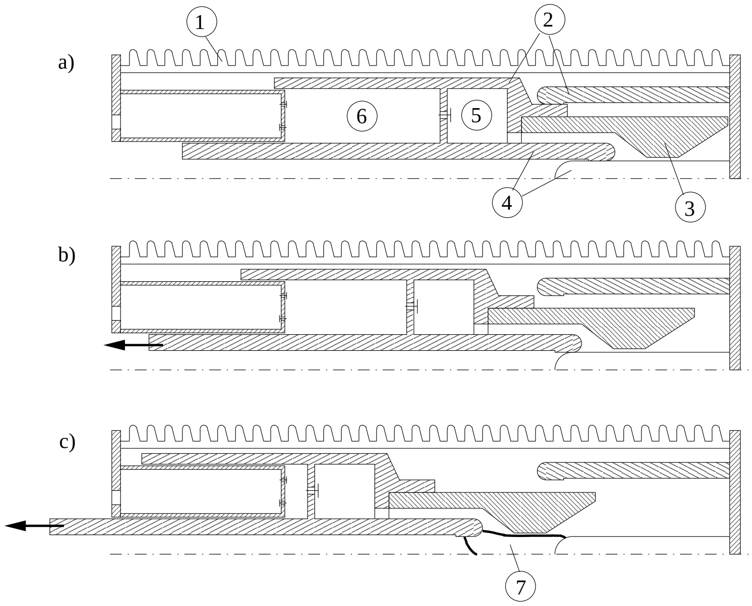

Figure 1.1. Working principle of a self-blast circuit breaker with pre-compression. 1: Porcelain insulation. 2: Main contacts. 3: Teflon nozzle. 4: Arcing contacts. 5: Self-blast volume. 6: Puffer volume. a) closed position, b) main contact open and c) arcing contact open.

current is directed through the arcing contacts (4). At this point, compression of the gas in the puffer volume (6) starts.

When the contacts are separated further (c), the arcing contacts open and the current continues to flow through an arc (7) which is initiated within the insulating Teflon nozzle (3). Due to strong radiation from the arc, material is ablated from the wall of the Teflon nozzle. This generates a high pressure in the nozzle and in the self-blast volume (5) at high currents. Thus, the pressure build-up is given by a combination of compression of the gas in the puffer volume and ablation.

The purpose of the puffer is to generate sufficient pressure when low currents are interrupted as the pressure generated by the arc is not enough for its extinction. When high currents are interrupted, the valve between the puffer volume and the self-blast volume closes as the pressure generated by the arc is enough. A spring-loaded valve in the puffer volume opens to limit the pressure there, and thereby minimize the energy needed to operate the breaker.

Approaching current zero, the high pressure built-up in the puffer volume results in a strong gas flow out of the self-blast volume and into the nozzle, reaching supersonic speed. The intention is to rapidly cool the arc and remove hot conducting gases from the arcing chamber.

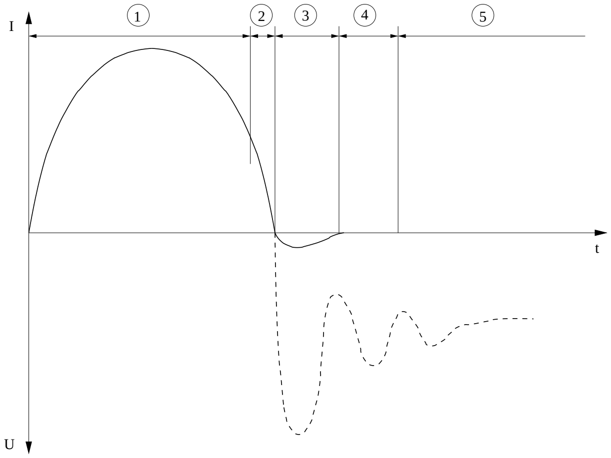

Figure 1.2. Illustration of the current, —, and the recovery voltage, - - -, as functions of time during current interruption. 1: High current phase, 2: low current phase, 3: thermal phase, 4: hot dielectric phase and 5: cold dielectric phase.

The different steps in the current interruption process are summarized in figure 1.2. The figure shows the current and the recovery voltage as functions of time during successful interruption. In the high current phase (1), the contacts are separated and pressure is built up in the self-blast volume, using mainly the power from the arc. During the low current phase (2), just before current zero, the energy input to the arc diminishes and the flow is directed into the nozzle. At current zero, the current is interrupted and the thermal phase (3) starts. Hot conducting plasma still remains between the contacts allowing a small post-arc current to flow due to the rapidly rising recovery voltage. If the power input by this current is smaller than the cooling rate, the breaker will interrupt thermally. Otherwise, the arc reignites and the current continue to flow.

When the circuit breaker succeeds to interrupt thermally, it has to withstand the recovery voltage, which can be $40-60\%$ higher than the supply voltage due to oscillations in the network. In this regime, which is called the hot dielectric phase (4), the gas is no longer conducting and the density is increasing as the temperature decreases, improving the voltage withstand capacity. Finally, the cold dielectric phase is entered and the breaker has successfully interrupted the current.

It has been shown experimentally by Knobloch and Habedank [1] that a criterion for thermal interruption can be obtained from the resistance of the arc at current zero. This limiting value of the arc resistance is independent of breaker geometry. Smeets and Kertész [2] used an empirical model to describe the transient evolution of the arc resistance. The model can predict the margin to reignition which can be correlated to the arc resistance at current zero.

Thus, it is clear that the conditions in the arc at current zero are important for breaker performance. The plasma can be contaminated with metal impurities during the high current phase, which remain at current zero. These impurities originate from the contacts which are usually made of a sintered mixture of copper and tungsten. Due to the strong dissipation of power at the arc-contact boundary, the contact surface melts, evaporates or even cracks. This erosion of the contacts generates metal impurities that may reach into the arc core. According to Taylor et al. [3], thermal reignition can be directly correlated to tungsten particles ejected from the contacts near current zero if the peak current is high. Proper design of the breaker, to reduce contact erosion, can avoid this phenomenon.

From dielectric point of view, molten droplets or solid particles ejected from the contacts may cause the breaker to fail due to local concentrations of the electric field.

When metal vapour is introduced in the arc, the properties of the plasma change in several ways, as discussed by Paul et al. [4]. At low temperatures ($< 10\ 000K$), metal impurities will increase the electrical conductivity of the plasma. The thermal conductivity is also affected at high metal concentrations. These properties are important for the interruption performance of the circuit breaker as they affect the conductance of the arc channel at current zero, and thus the thermal recovery of the arc.

According to Frind et al. [5] metal vapour from the contacts reduces the thermal recovery speed with as much as 50% due to the low ionization energy of metals. At low current and temperature, the principal effect of metal vapour is to add free electrons and thereby increase the electrical conductivity. For higher temperatures, metal vapour increases radiation affecting the pressure build-up in the nozzle. Airey [6] concluded that metal vapour has a significant influence on the energy balance. Before the current peak, the energy loss is dominated by convection. After the current peak, when the amount of metal vapour is high, radiation is the dominating cooling mechanism.

Interaction between the electric arc and the contacts is therefore of decisive importance in circuit breaker development. Yet, little has been done to take this into account in development tools for breakers.

Interaction between the arc and the Teflon nozzle, ablation, also generates a large amount of impurities (C_2F_4) in the arc during the high current phase. These impurities also modify the plasma properties and have to be taken into account during simulation of the interruption process.

The aim of this thesis is to investigate how metal impurities, generated during the high current phase of current interruption, are distributed in the electric arc and to derive simplified relations that can be used in industrial circuit breaker development to estimate the effect of contact erosion and thus reduce the number of tests needed during the development process.

The investigation focuses on processes occurring during the high current phase. Impurities generated during this period of time greatly influence the composition, and therefore the conductance, of the arc channel after current zero.

The thesis is based on four papers that can be read independently. **Paper 1** deals with calculation of the thermodynamic properties of $SF_6 - N_2$ mixtures, necessary for numerical simulations of the arc during the high current phase.

Influence of molten metal droplets ejected from the contacts on the flow fields and the distribution of metal vapour in the arc is studied with the aid of CFD (computational fluid dynamics) in **paper 2** and **paper 3**. The information is used to take a first step towards a simplified model taking this effect into account.

A model to describe cathode evaporation is developed in **paper 4**. The aim is to use the model in future work for studying the influence of contact evaporation in transient simulations on a complete commercial circuit breaker. The model also gives important boundary conditions for a model of contact erosion, i.e. the heat flux from the arc to the contact.

The thesis is organized in the following way. In chapter 2, important issues regarding modelling of the electric arc are discussed, relevant literature is reviewed and connected to the present work. The papers are presented in chapter 3 and the thesis is summarized in chapter 4. In the following parts, all papers are included. Minor changes to the format have been made, compared to the published or submitted versions, in order for the papers to conform to the thesis.

Chapter 2

Modelling the switching arc

2.1 The arc column

The arc is a self sustained discharge which is characterized by a low voltage drop. Power input from the current is balanced by convection, conduction and radiation and the relative importance of these effects depends strongly on the gas in which the arc is burning.

When the current is turned off, the plasma decays. This means that the temperature decreases and the species that constitute the plasma start to recombine. After some time, all particles have recombined and the plasma becomes a non-conducting gas.

SF_6 is used in circuit breakers due to its ability to absorb energy at low temperatures, around $2000K$, when the molecule is dissociated. This has a strong influence on the thermal conductivity and the specific heat, and therefore the decay rate of SF_6 is high compared to other gases.

The plasma in the main part of the arc, away from the boundaries, is usually considered to be in LTE (Local Thermodynamic Equilibrium) during the high current phase. This means that each point in the plasma is in its own local equilibrium where collisional and radiative processes are balanced by their inverse processes. Thermodynamic laws can be applied based on the local state in each point.

If radiative processes are interacting with collisional processes, changes in the system are fast or gradients in thermodynamic quantities are large, the plasma is out of equilibrium. This occurs at the arc boundary, near current zero or near the contacts.

Two types of deviation from LTE are usually considered, Chemical non equilibrium and thermal non equilibrium. Chemical non equilibrium is considered at current zero when reaction kinetics becomes important and near the contacts where electrons are ejected into or removed from the plasma. Thermal non equilibrium is of importance where temperature gradients or gradients in the electric field are high, i.e. near the contacts and the arc boundary. It is taken into account by considering different temperatures of atoms, ions and electrons.

As an example, Girard et al. [7] developed a two-temperature model of SF_6. The aim of the model was to use the reaction rates as source terms in hydrodynamic simulations with one transport equation for each species.

Today's gas-blast breakers use SF_6 or mixtures of SF_6 with N_2 or CF_4 as interruption medium. In addition, ablated nozzle material, C_2F_4, and evaporated contact material, Cu and W, contribute to the composition of the arc. LTE properties are needed in a wide range of pressure and temperature for the high current phase. Usually a temperature interval of $300 - 30000K$ and a pressure range of $1 - 100bar$ is sufficient. LTE properties of various combinations of some relevant substances have been calculated by several authors, e.g. [8, 9, 10, 11]. Details of such calculations for $SF_6 - N_2$ mixtures can be found in **paper 1**.

One of the most important plasma properties in circuit breaker arc modelling is radiation. This is also the most complex property as it depends not only on the local pressure and temperature, but also on the incident radiation from other parts of the plasma.

As circuit breaker arcs have a nearly cylindrical shape, the net emission coefficient, ϵ_N, has become popular due to its ease of use and acceptable accuracy. It was first introduced by Lowke [12] and it represents the radiated power per unit volume and solid angle that escapes radially from a plasma of radius R. It is assumed that the plasma is cylindrical, isothermal and in LTE. This coefficient has been calculated for some relevant gases by, e.g. Liebermann and Lowke [13], Gleizes et al. [14] and Aubrecht and Gross [15]. The net emission coefficient was used in the two-dimensional CFD simulations in **paper 3** together with an assumption of how absorption of radiation is distributed in the arc.

Alternative methods also exist. They are generally more detailed but also more difficult to implement. The method of partial characteristics, developed by Sevast'yanenko [16], results in two material parameters Som and ΔSim which are functions of local temperature pressure and the length of the line segment under consideration. The two parameters can be stored in tables and used in hydrodynamic calculations. This method was used for SF_6 arc plasmas by, e.g. Aubrecht and Lowke [17] and Raynal et al. [18].

2.2 Arc-contact interaction

The near electrode regions are characterized by strong deviations from LTE and a high electric field in a very thin sheath at the electrode surface. Typically, the electric potential can change $\sim 10V$ in only a few μm from the surface. This is large compared to the voltage drop across the arc column. Figure 2.1 shows schematically the variation of the electric potential in an arc discharge. The size of the near contact zones is greatly exaggerated for clarity.

The function of the anode is to collect electrons from the surrounding plasma. The heavy particle temperature changes from the plasma temperature in the arc

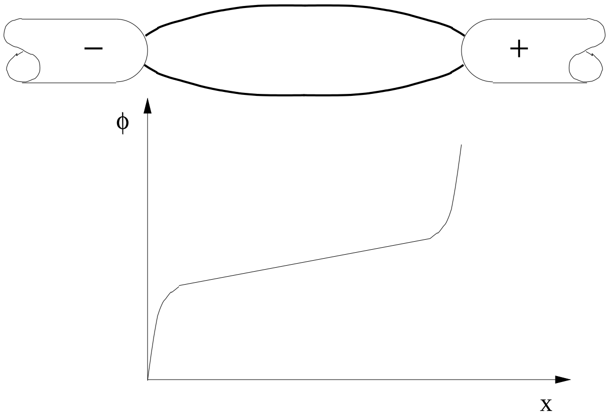

Figure 2.1. Variation of the electric potential, ϕ [V], in an arc discharge.

to the temperature of the anode surface, which is of the order of $1000K$. The electron temperature changes only slightly in front of the anode. The thin sheath at the anode surface is usually divided into a negative space charge zone closest to the surface and an ionization zone, connecting the space charge zone to the equilibrium plasma.

Jenista et al. [19] modelled the anode region in two dimensions, taking chemical (ionization) and thermal non equilibrium into account. It was found that the main driving force of the current is the strong electron density gradient. Thermal diffusion of electrons was found to be small. The main contributions to the heat flux into the anode are electron condensation on the anode surface, electron enthalpy flux and heavy particle conduction.

Similarly, Tanaka et al. [20] presented a one dimensional model. Also in this case, the main contributions to the current were diffusion of electrons due to the concentration gradient. The voltage drop near the anode was found to be either positive or negative depending on the current.

The cathode region is somewhat more complicated than the anode region and it is considered to be the most active region in the arc. The role of the cathode is to emit electrons to the surrounding plasma. The emission mechanism is usually considered to be thermoionic field emission (see, e.g. [21, 22]) but seems to be a source of disagreement even to this date. As at the anode, the heavy particle temperature gradient is high.

Current transfer near the cathode is not determined only by the emission mechanism but also by the space charge zone which is a collision-less layer at the vicinity of the surface. This zone has a positive voltage drop as the plasma is not neutral. Thus, ions are accelerated to the surface transferring their kinetic energy and ionization energy to the wall. Emitted electrons are accelerated away from the surface and electrons in the arc column may have enough energy to overcome the field and reach the wall, e.g. "back diffused electrons". Production of ions and transition from the highly non equilibrium plasma in the sheath to the equilibrium plasma in the arc is ensured by the ionization zone, located between the sheath and the equilibrium plasma.

Several works considering the near cathode region exist in literature. Morrow and Lowke [23] proposed a one dimensional model assuming thermoionic emission, neglecting the space charge zone and evaporation of cathode material. This work included back diffused electrons due to ambipolar diffusion.

Zhou et al. [24] proposed a more detailed model which included the space charge zone. Here, thermoionic field emission was assumed and evaporation of the cathode material was included in a simplified manner. It was found that cathode erosion depends strongly on the work function and the vapour pressure of the material.

Kaddani [25] modelled the complete system of cathode, arc and anode at atmospheric pressure. The work included a detailed description of the anode and cathode regions including space charge zones at the near vicinity of the electrodes. The methodology used, showed that high pressure arc properties could be predicted accurately using numerical simulations.

Benilov and Marotta [26] presented a model for the near cathode region of atmospheric pressure arcs, taking details of the space charge zone and the ionization zone into account.

In **paper 3**, the model of Benilov and Marotta [26] is extended to wide pressure range by coupling with a model for evaporation of the surface developed by Benilov et al. [27]. Evaporation is found to be an important component of the energy balance at the surface.

Knowledge of erosion mechanisms in electrical contacts is important as it determines the lifetime of the contact and metal impurities eroded from the contacts can, under the right circumstances, reach far into the arc. As discussed in the introduction, several mechanisms may be important, e.g. evaporation, melting of the material with ejection of metal droplets, and cracking due to thermal chock with ejection of solid particles.

The type of sintered $Cu - W$ contact which is used in high current circuit breakers has been investigated experimentally by, e.g. Gessinger and Melton [28] and Hori et al. [29]. It can be seen that this type of contact is eroded by evaporation of copper. After a number of operations, only the empty tungsten matrix remains at the surface. It is brittle and fractures easily, which may result in ejection of molten or solid metal particles.

As contact erosion depends heavily on the strong interaction with the arc, detailed knowledge about the anode and cathode regions is necessary to understand the process and has not been known until recently. At this time, no complete model for contact erosion is available. It is mainly investigated experimentally and is usually presented as eroded mass per operation as a function of current or arc energy, see Walczuk [30]. This type of information might be sufficient when contact life time is to be estimated. However, it is not enough when studying the influence of contact erosion on the performance of a circuit breaker and it does not give detailed information about which mechanism is active at different times during the current cycle.

Chévrier et al. [31] modelled evaporation of the contacts in a SF_6 self-blast breaker using a two-dimensional hydrodynamic model of the arc. The arc-contact interaction was modelled in a very simplified way, not taking details of the near-contact layers into account. The spatial distribution of copper vapour in the arc was qualitatively compared to experiments.

A mathematical model taking evaporation, ejection of molten metal droplets and ejection of solid particles into account was presented by Kharin [32]. The model focuses on details in the contact, such as formation of a liquid metal pool and crack formation at the surface.

In **paper 2** and **paper 3**, the influence of molten metal droplets ejected from the contact during the high current phase is investigated by a parametric study with the initial droplet size and speed as parameters. The effect of the droplets on the flow field and the distribution of metal vapour from the droplets is found to be significant.

2.3 Circuit breaker arc models

The arc is usually modelled using the magnetohydrodynamic equations, i.e. the compressible Navier-Stokes equations and Maxwell's equations, at some level of simplification.

The earliest attempts to analyse circuit breakers with mathematical models were made by Cassie [33], Mayr [34] and Browne [35]. These arc models are based on ordinary differential equations describing the evolution of the arc conductance in time. As the high and low current phases have significantly different time scales, they may be separated. Mayr's model concerns the high current phase, and Cassie's the low current phase. Browne combined the two to a unified theory.

More detailed models have later been developed. One branch of models is the two-zone approach, initiated by Lowke and Ludwig [36]. It was modified for ablation controlled arcs by Ruchti and Niemeyer [37] and Müller [38].

The region within the nozzle is divided into two isothermal zones; The arc and the surrounding vapour layer generated by ablation. In the original model by Lowke and Ludwig [36], conservation equations of mass, momentum and energy are integrated over each zone in the radial direction. The result is a set of quasi stationary one-dimensional equations in the axial direction for the arc temperature, pressure, electric field and arc radius. These models are valid in the high current phase when ablation is a dominant mechanism and turbulence and thermal conduction can be neglected.

Another group of models is the integral approach, first introduced by Cowley [39]. Here, the magnetohydrodynamic equations are integrated in the radial direction under the assumption that boundary layer theory is applicable. The cold gas flow, outside the arc, is assumed to be adiabatic, one dimensional and inviscid.

A set of six transient, one-dimensional, differential equations in the axial direction are obtained. The equations are dependent on a set of shape factors consisting of normalised properties integrated along the radius and normalized by the thermal influence cross section of the arc. The set of equations has the unknowns free stream density, enthalpy, velocity and electric field together with eight shape factors. To solve the equations, some of the shape factors must be determined experimentally. In [40], two examples are given on the use of the integral method.

The effect of wall ablation was investigated by Fang and Newland [41] using the boundary layer integral method and the influence of different gases, nozzle materials and electrode materials was discussed. A circuit breaker arc was also investigated by Park and Fang [42] using this type of model. The nozzle is connected to a compression chamber and gas leakage is included. The model includes two shape factors, which need to be determined on experimental basis or by experience.

During the past decade CFD models have become more realistic alternatives to the simplified models due to accelerating computer performance. These models generally solve the magnetohydrodynamic equations in axi-symmetric configurations using, e.g. finite volume or finite difference methods. They offer the possibility to study complex geometries with moving parts and detailed boundary conditions.

Yan et al. [43] implemented a full axi-symmetric arc model into a commercial CFD package. The model included magnetic forces, ablation and turbulence. It was applied during both the high current phase and the current zero period in an SF_6 circuit breaker.

The model by Zhang et al. [44] used in **paper 3**, was developed for unstructured grids. Special attention is paid to radiation. The net emission coefficient is used but the distribution of absorption within the arc is calculated as a function of local pressure and temperature.

Due to long computation times, and lack of robust commercial solvers, integral tools are still used for industrial circuit breaker design.

Chapter 3

Summary of papers

3.1 Paper 1

T Nielsen and A Kaddani 2001 “Thermodynamic Properties and Electrical Conductivity of $SF_6 - N_2$ Mixtures in the Temperature Range of $300 - 30000K$”, Technical Report TRITA-MEK 2001:08, KTH, Stockholm

The aim of the report is to calculate the thermodynamic equilibrium properties of an $SF_6 - N_2$ plasma in a wide range of pressure and temperature. These data are also available in literature. The calculations were performed in order to have complete control over which methods are used and to be able to calculate the properties of any given mixture.

It was found that mixing N_2 into SF_6 has little influence on important properties such as enthalpy, specific heat, speed of sound, compressibility and density if the amount of N_2 is less than 90%. This is important in circuit breaker applications for two reasons. First, SF_6 has negative effects on the environment and the amount of SF_6 must be minimized or replaced with alternative gases. Second, there is a problem with condensation of SF_6 in severe weather conditions, i.e. low temperature. This problem is reduced by mixing with N_2 or CF_4.

The data was calculated using a first order correction of the equation of state due to coulomb interaction between charged particles. The validity of this assumption was checked and it was found that the correction is valid between 1 and $100bar$, which is sufficient for circuit breaker applications.

The methodology that is presented in the report has later been used to calculate the properties of $SF_6 - N_2 - C_2F_4$ mixtures, used in **paper 2** and **paper 3**.

3.2 Paper 2

T Nielsen, A Kaddani and S Zahrai 2000 “Metallic Vapours and Droplets in Ablation Controlled Electric Arcs”, *Proc. 13ht Int. Conf Gas Discharges and their Applications* (Glasgow: University of Strathclyde), Sept. 2000

The conference contribution initiates the work of studying the role of metal droplets, originating from the contacts, in a gas-blast circuit breaker arc. Such droplets may evaporate strongly along their path through the arc and contribute significantly to the amount of metal vapour in the arc. This phenomenon is usually not considered in gas-blast breakers. In vacuum breakers, it is well known that this problem exist, see Daalder [45], and that it influences the interruption performance. Several authors mention the possibility of ejection of metal droplets in gas-blast breakers as the measured contact erosion cannot be explained by evaporation alone.

Models for contact erosion usually take only evaporation into account. As a first step, it was therefore necessary to parametrize the erosion in terms of mass flux, initial droplet size, initial droplets speed and initial droplet temperature. A parameter range giving significant vapour contribution was chosen.

The influence of evaporating metal droplets on the flow field in an electric arc is discussed in the paper. The results showed that the initial size and speed of the droplets determine if there will be metal vapour in the arc or not. It is observed that large droplets may travel upstream from the contact and generate vapour throughout the arc. A simplified model was suggested to determine what droplet sizes and speeds are significant. The intention is that such a model can be used in integral tools for circuit breaker development to determine if droplets might be present.

The results highlight the potential significance of metal droplets. The work is continued by more detailed modelling of the droplets and the electric arc in the next paper.

3.3 Paper 3

T Nielsen, A Kaddani and S Zahrai 2001 “Modelling evaporating metal droplets in ablation controlled electric arcs”, *Accepted for publication in J. Phys. D: Appl. Phys.*

The paper is a continuation of the work on evaporating droplets in gas-blast circuit breaker arcs initiated in **paper 2**. Here, a state of the art, two-dimensional arc model developed for CFD is used. The molten metal droplets are modelled in detail taking the influence of varying plasma properties, radiation heating and cooling of the droplets and influence of evaporation on the drag force into account. Other effects such as cooling of the droplets due to electron emission, heating due to electrons arriving at the surface and heating due to recombination of ions at the surface are neglected but the potential influence is discussed extensively.

A large number of cases are run for different values of the initial droplet size and the initial droplet speed in order to study the influence on the temperature field, the velocity field and the distribution of metal vapour. It is found that there is a range of parameters for which the amount of metal vapour in the arc is significant. Due to the energy needed for evaporation, the temperature in the arc is lowered significantly locally where the droplets reach their boiling point and evaporate. The influence on radiation from the plasma due to contamination of metal vapour is also investigated and the temperature is found to be significantly lower where the vapour concentration is high. Despite this strong local influence, the effect on measurable quantities like arc voltage and stagnation pressure is hardly measurable. This means that detailed experimental investigations would have to be performed in order to detect the droplets and correlate them to failure of the breaker.

The simplified model proposed in **paper 2** is extended to also include heat transfer to the droplets due to radiation. It is evaluated against the CFD results and the agreement is found to be good.

3.4 Paper 4

T Nielsen, A Kaddani and M S Benilov 2001, "Model for Arc Cathode Region in a Wide Pressure Range", *Accepted for publication in J. Phys. D: Appl. Phys.*

The paper presents a detailed study of the near cathode region. The one-dimensional model of Benilov and Marotta [26], taking the space charge zone and the ionization zone into account, is extended to wide pressure range by coupling with a model for evaporation developed by Benilov et al. [27]. Heat and current transfer between cathode and the plasma is studied in detail in terms of individual contributions from electron current, ion current and evaporation for a wide range of pressure and temperature.

The results show that contact evaporation plays a major role when calculating the heat transfer to a copper-tungsten cathode. In the major part of the temperature-pressure range, the gas at the cathode surface consists of 100% metal vapours. This means that heating of the cathode due to recombination of ions at the surface is reduced due to the low ionization energy of metal atoms.

Conductive heat flux inside the cathode was found to have negligible influence on the wall temperature at pressures relevant for circuit breakers. This implies that the energy equation does not need to be solved in the cathode in order to calculate the evaporation rate and the wall temperature. This is an advantage when the near cathode model is used as a boundary condition for flow calculations in a circuit breaker.

Heat flux to the cathode is a fundamental variable needed when a model for contact erosion is developed. This work makes it possible to study the effect of cathode evaporation in two-dimensional hydrodynamic simulations of circuit breakers.

Chapter 4

Concluding remarks

The possibility of molten metal droplets ejected from the contacts of a high voltage circuit breaker has been investigated by means of computational fluid dynamics. As no model is available for this phenomenon, a parametric study was performed to study the potential impact of evaporating droplets on the velocity field, temperature field and distribution of metal vapour in the electric arc.

It was found that droplets of initial sizes and speeds, likely to appear in a circuit breaker arc, will generate significant amounts of metal vapour. A simplified relation has been suggested to take the effect of droplets into account in simplified arc models used in practical circuit breaker development.

The results suggest that a model for ejection of droplets or solid particles from the contacts should be developed. To initiate this work, a model for the near cathode region is presented, giving the heat flux to the cathode and the amount of metal evaporated from the cathode surface in a pressure range of interest in circuit breakers. This information is essential for further development of a contact erosion model.

The model for cathode erosion may also be coupled to transient CFD simulations or included in a simplified integral model to take into account the effect of contact evaporation on circuit breaker performance.

The continuation of this work will include such studies, combined with experimental investigations, to obtain a better understanding of the influence of metal impurities on circuit breaker performance.

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