Future Perspectives on High Voltage Circuit Breaker Research

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The research on high voltage circuit breakers using SF_6 is addressed. An overview of current state of research in this field will be given and possible future research directions will be discussed on examples. Such directions are, for example, the radiative energy transport, the understanding and description of ablation processes at the nozzle and contact surfaces, the influence of ablated vapors on pressure build up and interruption capability, the electric breakdown processes, departures from equilibrium, turbulence and the importance of magnetic fields and 3D modelling.

Keywords: arc, circuit breaker, high voltage, SF_6

1 INTRODUCTION

Circuit breakers are important devices in electrical networks which ensure safe power flow [1],[2]. They have to interrupt normal load and short circuit currents in the range of several kA and several 10…100 kA, respectively. They also have to be able to connect parts of the network, i.e. close on normal and short circuit currents. After current interruption, the network voltage has to be safely withstood. These voltages range from a few 100 V to several 100 kV. In distribution networks at low voltages (<1000 V) mostly air circuit breakers are used. In distribution networks at medium voltage level (<72 kV) gas circuit breakers (SF_6) and increasingly vacuum circuit breakers are used. In high voltage sub-transmission (<145 kV) and transmission levels (> 145 kV) mainly gas circuit breakers (GCB) using SF_6 are used [1]. All these devices employ an electric arc for interruption of the current at current zero (CZ). In the present contribution the focus will be on HV gas circuit breakers, using SF_6. Many important aspects of the technological challenges are, however, also applicable to other types of circuit breakers and alternative gases to SF_6. An overview of research directions in the field of HV circuit breakers was given recently [3]. The present contribution summarizes the main directions and gives examples. Section 2 gives a technology overview, section 3 gives an overview of the different topics of interest, questions, and barriers to future success.

2 TECHNOLOGY OVERVIEW

Examples of modern SF_6 high voltage gas circuit breakers are shown in figure 1. Depending on the application these devices are either encapsulated in grounded metal housings (Gas insulated switchgear) or have insulating housings, so-called live tank circuit breakers. For the highest current ratings, which are needed close to generators with nominal voltages in the range of a few 10...30 kV, generator circuit breakers are used [4].

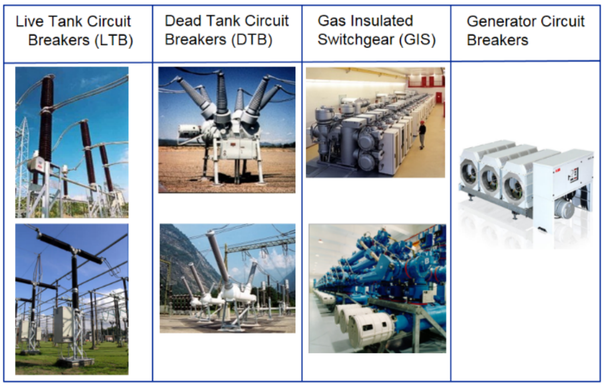

Fig. 1: Example of HV circuit breakers

Beside the differences in external insulation, these devices have common design features, which are shown in figure 2 using the example of a so-called self-blast or auto-expansion CB [1],[5]. The SF_6 fill pressure of such devices is typically in the range of 0.43…0.7 MPa (absolute). In the “closed” contact position, the current flows in the nominal contact system. During an opening operation this current commutes to the arcing contacts. Following the separation of the arcing contacts, an arc is ignited between plug and tulip contacts, surrounded by the nozzles. This is referred to as the arc zone. Usually polytetrafluoroethylene (PTFE) with some fillers is used for the nozzle material. The arc elongates in length with time due to the contact movement and needs to be extinguished at a CZ crossing of the applied current. This is achieved by a gas flow which cools the arc by convection and turbulence [5]. At low applied currents, e.g. normal load currents, this gas flow is produced by a pressure rise in the compression volume (CV), see figure 2.

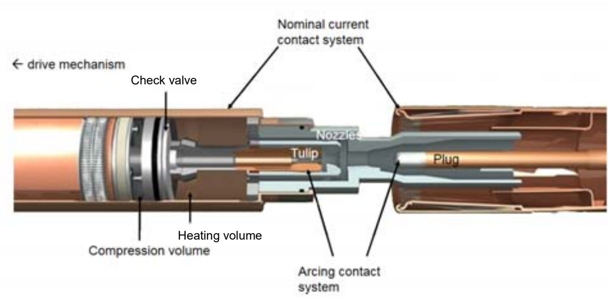

Fig. 2: Arc zone of a typical HV self-blast CB in open contact position

During the opening operation, this volume is shrinking in size, creating an over-pressure. Via a check valve, this pressure is applied to the heating volume, producing a gas flow towards the arc zone. At sufficiently high currents the pressure in the arc zone can be higher than in the heating volume. In this case, ablated polymer vapor can flow to the heating volume, which is referred to as back-heating. A typical example of pressure rise in the heating volume, current and arc voltage during the interruption process is shown in figure 3. In the case of self-blast CBs, the check valve separates the CV from the heating volume during back-heating, which decouples the pressure forces in the heating volume from the drive mechanism. This allows to use drive mechanisms with lower energy requirements. In so-called puffer circuit breakers there is no such separation, i.e. only a compression volume exists, which is then equal to the heating volume [1]. Besides the flow into the heating volume, the arc energy flows into the sufficiently large dimensioned exhaust volumes (not shown in figure 2). When the current reduces during the back-heating process towards CZ, conditions for the reversal of the flow can occur, i.e. gas from the heating volume can flow towards the arc zone, leading to a reduction of the pressure in the heating volume, see figure 3. This leads to a transition from an ablation controlled arc to a convectively stabilized arc, which is accompanied with a transient change of the pressure and temperature distribution in the arc zone and its surroundings. This phase is referred to as the flow reversal phase.

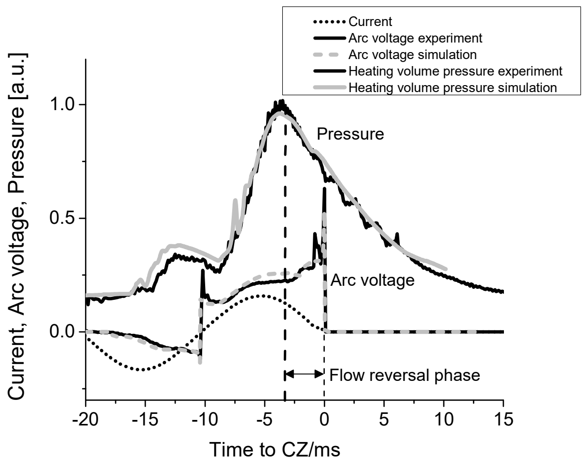

Fig. 3: Typical example of measured and simulated waveforms of current, pressure build up in the heating volume and arc voltage of a self-blast CB (by courtesy of Mahesh Dhotre, ABB Switzerland Ltd). For details of the simulations see [4]

Within the first microseconds after current zero, the current interruption is determined by the competing processes of arc conductance decay and the rise of the applied voltage, which drives a current ("post arc current") through the still conductive (temperatures around 5000…12000 K) plasma channel [1],[5],[6]. This is referred to as the thermal interruption phase. Once the conductance of the plasma channel drops to a level where no significant heating due to the post arc current can occur, the voltage rise of the network in form of the transient recovery voltage (TRV) has to be withstood. This rise occurs within several ten to several hundred microseconds. Due to the elevated temperature (several thousand Kelvin) of the plasma channel after CZ there is only a limited voltage withstand during this phase. This is referred to as the "dielectric recovery" phase. If the voltage withstand is not sufficiently high, a dielectric failure occurs. This can happen in the former arc channel during the early dielectric recovery within less than 100 μs after CZ, typically. During the later dielectric recovery, it is completely independent of the previous arc channel [7]. For the interruption process the control of the arc conductance decay around CZ is a crucial mechanism for thermal interruption and early dielectric recovery as well. This decay is mainly linked to the pressure in the arc zone at CZ, the convective cooling due to strong pressure gradients and the development of turbulence at the arc boundaries [5]. It can be influenced by the presence of metal vapor. During the dielectric recovery, the control of the electric field, the pressure, the temperature and the gas composition (SF_6, polymer vapors, metal vapors) in the arc zone is decisive for successful interruption. This needs careful design of the capacitive electric field, the gas flow field in the breaker and control of polymeric and contact material ablation (e.g. [8],[9],[10],[11],[12]).

3 IMPORTANT TOPICS IN HV CIRCUIT BREAKER RESEARCH

In the last two decades, progress has been made towards covering higher short circuit current and voltage ratings accompanied by a reduction of size and drive energy. In the circuit breaker development process this needs a sufficiently precise prediction of pressure, temperature, contact and nozzle ablation and their distributions in the CB by simulations based on computational fluid dynamics (CFD). Such simulations for gas CB use compressible gas dynamic equations (e.g. Navier Stokes equations) in a single fluid approximation, where the thermodynamic and transport properties depend on pressure, temperature and composition (e.g. [4]). In this description, local thermodynamic equilibrium (LTE) is usually assumed. In most cases, these simulations are done for axis-symmetric geometries, i.e. in 2D approximation. There are a number of phenomena which are still modelled in a simplified way, for example radiative energy transport (RET), turbulence, electrode and nozzle ablation and departures from the equilibrium. Thus, modelling and validations are important issues in the research of HV circuit breakers. In the following, the main research topics will be shortly discussed on examples.

3.1 RADIATION

Radiation is the most relevant arc cooling mechanism in the high current phase. It leads to ablation, which in turn influences the pressure build up. Around CZ it determines the arc temperature profile, which determines the arc conductance and temperature decay. Significant progress has been obtained in the field of radiative energy transport modelling by use of discrete ordinate method (DOM), the P1 method, and net emission coefficients (NEC) models with suitable band averaging methods (e.g. see [13], [14], [15], [16], [17], [18]). Pressure build up in the heating volume and also in the exhaust volumes can in this way quite reliably be calculated (see e.g. figure 3). Metal and polymer vapors are often taken into account correctly in the thermodynamic and transport properties used for simulation. However, for the radiation properties this is still in an early phase [16] and often only SF_6 radiation data is used for the simulations. The good progress which has been achieved with the DOM in simulations of high voltage CB is accompanied with higher numerical effort since the RET has to be solved for the several directions and the various bands. Much less numerical effort is needed for the P1 model, which approximates the radiation by first-order spherical harmonics. This approximation is suited for optically thick media with large absorption coefficients. In circuit breakers this method alone is not sufficiently accurate. As it has been shown recently it may be used in combination with the DOM to reduce computation time [15]. Net emission coefficient models (NEC) are based on emission only and are of low computational effort. They were used frequently in the past and need to introduce absorption in an empirical way, which generally reduces the accuracy for circuit breaker applications, especially when describing regions far from the arc, e.g. the exhaust or the cooling of the plasma in the heating channel and volume. Thus, the most advanced treatment of radiative energy transport to date is the use of DOM, or a combination of DOM with the P1 approximation. Since these approaches are still consuming a large amount of the computational time, new, more computationally efficient approaches should be investigated, e.g. as discussed in [17], taking into account higher moments than the P1 model. Such efficient numerical approaches are of high importance, especially when taking into account the need for 3D type simulations. There are still large discrepancies in the radiation spectra used by different groups, which need further clarification. The spectra in the low temperature regions in the arc boundaries, e.g. where molecules are present, need special attention, since it will determine the arc temperature profile in the arc mantle and in the surrounding gas. This will be influenced by admixtures of metal and polymer vapors, e.g. copper and C_2F_4. The radiation modelling in the field should be, therefore supported by experimental validations under the conditions relevant for circuit breakers, e.g. at high pressures and the relevant temperatures and compositions, as e.g. shown in [19]. In this paper, copper dominated free burning arcs were investigated, which are relevant for low voltage CB. It was found that standard temperature determination methods based on the assumption of thin or thick plasma were limited and simulations of the spectra could give further insight.

3.2 CONTACT EROSION AND NOZZLE ABLATION

Polymer ablation (mostly PTFE in SF_6 HV CB) from the nozzle wall is important for the pressure build up due to nozzle clogging or backheating during the high current phase. The influence of the polymer ablation on the transition from the high current phase towards CZ, i.e. the flow reversal phase, is still less well understood than the back-heating phase. The polymer ablation may change in this regime due to absorption of radiation in cold SF_6 [11]. Significant wear of nozzles, as shown in figure 4 might lead to changes in the interruption behavior. The prediction of the shape change of nozzles is, therefore, of high interest for the development and life time predictions. The distribution of polymeric vapor may affect the dielectric withstand after CZ.

Metal vapor affects the radiation and the electrical conductivity of the arc, which may lower the interruption performance at and after CZ if present in sufficient quantity. Simulations usually contain source terms for polymer ablation (e.g. [4]). The contact erosion can be predicted by relatively simple models, e.g. [10], similarly to the polymer ablation.

Fig. 4: PTFE nozzle after arcing

An important mechanism for the understanding and description of distribution of metal vapor is the formation of droplets and their evaporation, see figure 5 for an example. This image was obtained in a simplified laboratory arrangement, where the arc plasma was extracted from the arc zone through a nozzle hole and injected into a free space. A large number of particles of different size and vapors can be seen. This may be a situation similar to what happens during back-heating in a self-blast circuit breaker. The effect of such particles/vapors on the interruption performance has to be taken into account. Droplet formation and evaporation in the arcing zone under HV CB conditions were studied theoretically by [20]. More investigations of this type in combination with measurements are needed for the various conditions in HV CBs. To validate simulations, experiments should be done where the distribution of metal vapor is determined along with the pressure and temperature fields. For copper-tungsten contacts the ratio between copper and tungsten vapor in the plasma is still not clear, and also needs experimental clarification, e.g. by spectroscopic investigations. Several groups investigated by simulations how copper vapor affects the radiation coefficients and electrical conductivity. However, for the thermal interruption only little information on the quantitative influence of metal vapor is published, e.g. [21]. For the dielectric recovery there is no experimental data available in SF_6 HV CB describing the relation between metal vapor and dielectric withstand. Quantitative data on such relations are needed, therefore. This could be done by combining theoretical assessment (e.g. [22]) and experimental investigations.

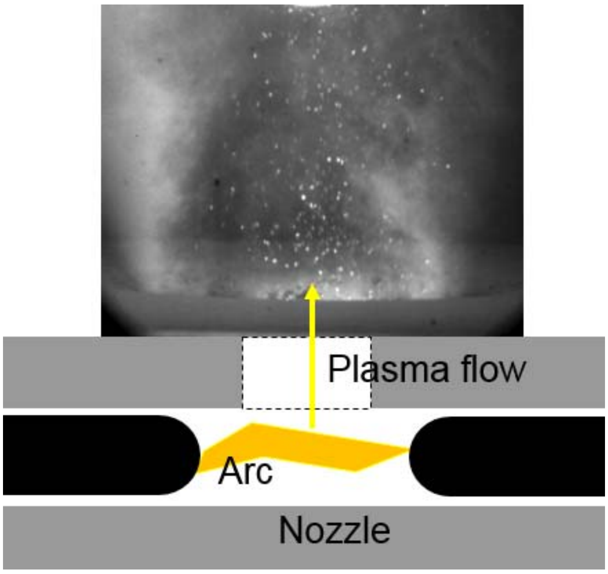

Fig. 5: Example of hot gas cloud produced by a 5 kA arc between Cu/W contacts in a PTFE nozzle. The hot plasma was exhausted upwards through a hole in the nozzle (15 mm in diameter). The set-up was placed in a GIS tank filled with SF6 at 2bar

3.3 TURBULENCE

Turbulence in arcs is generally still not well understood. In simulations of HV CB it is usually treated by Reynolds averaged Navier Stokes methods (RANS) using the k-ε model with various formulations [4],[12],[15] or by the Prandtl mixing length (PMLM) model, e.g. [23],[24]. Different approaches are used and some groups introduce fit parameters to the Prandtl mixing length model tuned to experimental data, as e.g. for reproducing the arc conductance [24]. All these models do not describe satisfactorily the CZ phase and the interruption phase. Turbulence at the CZ arc is produced by the shear flow at the arc boundaries due to the strongly differing velocities inside and outside the arc. This produces vorticity, which is transferred into the arc by turbulent eddies and efficiently cools the arc. Due to the 3D nature of this process (see figure 6 for an example) 3D large eddy simulation (LES) models might be better suited for simulation. However, the large computational effort makes using such a turbulence model currently still impractical in standard CB simulations. Simpler, more practical but sufficiently precise models have to be identified.

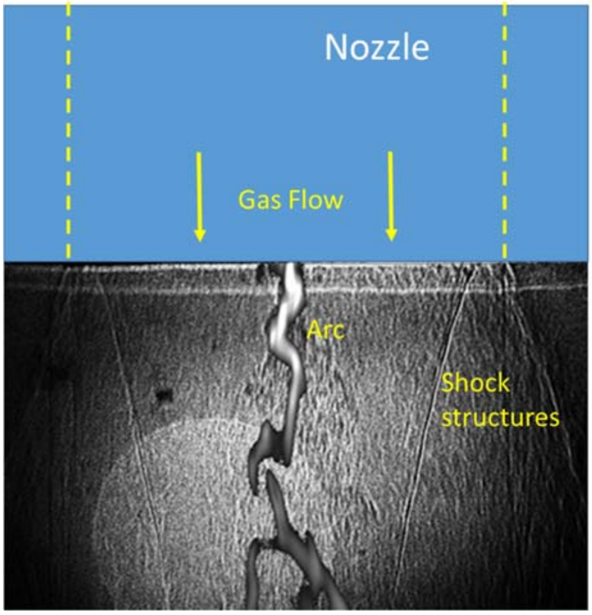

Fig. 6: Superposition of shadowgraph and light emission images of a turbulent 10A (DC) arc in an imposed flow at the exit of a PTFE nozzle (top of the figure). The inner diameter of the flow channel in the nozzle was 17 mm. The stagnation pressure was about 10 bar. The exposure time of the image was 2 μs. The flow direction was from top to bottom, indicated by the arrows. Shock structures of the flow can be seen in the shadowgraph image. The image of the light emission (gray scale) shows the 3D structure of the arc outside the nozzle (by courtesy of Emmanouil Panousis, ABB Switzerland Ltd)

The turbulence for low current arcs at CZ cannot be separated from the non-LTE issues which be discussed below, i.e. for the simpler models this has to be taken into account. For validation precise reference experiments are needed, where not only arc voltage and current is measured precisely close to CZ, but where also the arc temperature and conductivity distribution is addressed.

3.4 DEPARTURES FROM EQUILIBRIUM

The validity of the assumption of LTE is discussed widely in the field since decades. It is generally agreed that in the high current plasma this assumption is reasonable and only in the arc fringes some deviations might occur, e.g. [25]. For CB simulations these deviations have only little effect, such that inclusion of non-LTE effects in the high current phase are not of relevance for typical CB simulations. Non-equilibrium effects are probably most relevant for the CZ phase and early dielectric recovery. In [26] the influences of chemical non equilibrium on the arc decay were investigated, showing a significant difference in the species concentrations and higher cooling rate compared to the LTE assumption. The investigation of [25] used a two temperature model for electron and heavy particles. They observed significant deviation from thermal equilibrium when approaching CZ. As a result they showed that the arc conductance was higher in the case of non-thermal equilibrium. The arc conductance decay after CZ was experimentally investigated by [27] showing the large influence of delayed ion recombination on the conductivity decay. These examples show that the inclusion of chemical and thermal non-equilibrium is probably crucial to describe the arc conductance decay around and after CZ. This is probably even more complicated by the fact that the chemical and thermal non-equilibrium is coupled to the radiation and the turbulence, i.e. generally these processes cannot be treated separately. Suited simplifications are needed, therefore. This will need significant effort on simulations and experiments in the future. For validation of models sufficiently precise reference experiments in CB relevant geometries are needed, e.g. in two pressure devices, where stable flow conditions are applied from an external tank. In these experiments, not only the total arc conductance but also the distribution of arc conductance could be determined. This may be done either directly by electrical methods (e.g. capacitive coupled probes as shown in [28] and resistively coupled probes [29]) or by optical methods [30], e.g. see figure 7.

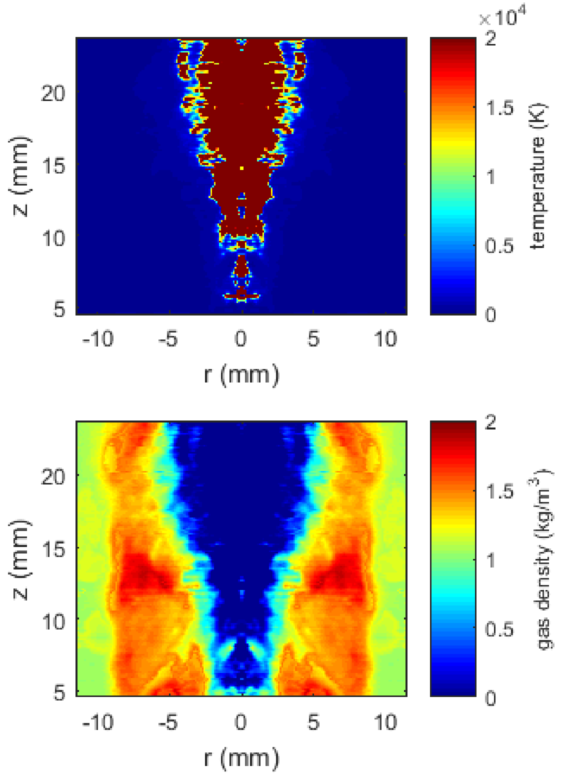

Fig. 7: Measurement of the gas density and temperature of an arc close to CZ. The arcing medium is air at ambient pressure and the arc is axial blown with an overpressure of 2.3 bar. The field of view is behind the stagnation point (in flow direction), where the nozzle system permits optical access to the arcing region and the flow is released into free space; for details of the method see [30]

3.5 ELECTRIC BREAKDOWN

For the electric breakdown at CZ, i.e. the thermal interruption phase, the arc energy balance around CZ is decisive. Reliable predictions for this phase are needed to reduce the expensive high power laboratory tests during development. This needs a correct description of the arc conductance taking into account turbulence and departures from equilibrium and composition, as discussed above. For predictions of the thermal interruption the arc conductance has to be coupled to network programs. In this way the arc-circuit interaction, i.e. the current and voltage deformation before and after CZ, respectively, can be calculated and the development of the arc conductance after CZ can be predicted. Such simulations still show significant deviations from the measurements and the full interruption process cannot be predicted with sufficient accuracy at the moment. Consequently, it is still not possible to replace expensive testing in high power laboratories by simulations of the full process. The dielectric recovery phase that occurs after current zero has been addressed in some publications in the recent years. Streamer and leader models can serve to describe the electric breakdown during the dielectric recovery in a CB, e.g. see figure 8.

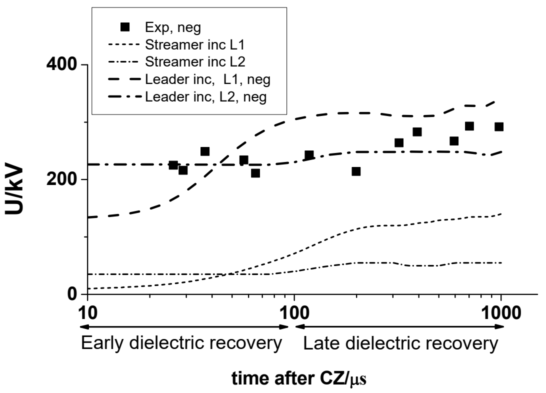

Fig. 8: Measured and simulated dielectric recovery (DR) in SF_6 after interruption of 23 $kA_{peak.}$, for details see [7]

The distribution of hot gases in the downstream regions of the flow, e.g. in the exhausts can be calculated and breakdown predictions agree relatively well with the measurements [31],[32]. Crucial is the knowledge of the temperature and pressure dependence of the critical electric field, which was calculated by several groups for SF_6 (e.g. [31]), but also taking into account the effect of PTFE admixtures [33],[34] and also Cu vapor [22]. Experimental validations of these calculations under the conditions found during the dielectric recovery, with gas temperatures typically below 4000 K, are challenging and only slowly progressing. Due to the complex conditions in HV CB (large spatial and temporal variations of pressure, temperatures and compositions) validations of models under the real conditions in circuit breakers are difficult and show large uncertainties. The dielectric breakdown under the conditions of high ion concentrations, i.e. space charges, elevated temperatures in combination with spatially largely varying particle number densities is not sufficiently understood and needs further experimental and theoretical investigations.

3.6 SF_6 ALTERNATIVES

As is well known SF_6 is a unique medium for arc quenching in HV CB [1]. These unique properties are the stability of the molecule, i.e. it recombines after decomposition in an arc; it is not toxic; it has a high heat capacity in the temperature range of interest for interruption (below 5000 K where electrical conductivity is low) and has a quite high critical electric field, resulting in a high dielectric withstand. Due to some of these unique properties it has, however, a large global warming potential of about 23900 (based on 100 year time horizon) [35] and is, therefore, under discussion for regulation of use. Suitable alternatives are investigated since more than a decade but no comparable alternative, i.e. an alternative which combines similar properties as SF_6, has been found. In some studies CO_2, e.g. [36] or CO_2 with some admixtures (e.g. [37]) is identified as a promising alternative. It must be noted, however, that its performance is inferior to SF_6. With improved understanding the CO_2 technology might be further optimized and the performance gap between SF_6 and CO_2 might become smaller. More research is needed for this and all the above discussed topics apply also for CB using CO_2. Recently wider research activities have been started, scanning the best gases for suitable properties, allowing mixtures of gases, e.g. [38]. All these investigations not only aim at finding a replacement gas for arc quenching, but also for pure insulation applications, e.g. in gas insulated switchgear and substations. Such investigations are important and should be continued. It has to be taken into account that complex mixtures of gases will in most cases not recombine to the original composition but produce other substances with possibly unwanted properties regarding toxicity, GWP and interruption/insulation performance for example. The properties of complex mixtures for use in HV CB may, therefore, change significantly over the lifetime. This needs further investigations.

5 CONCLUSIONS

The present contribution describes important issued in HV CB research. Progress has been achieved in the description of radiative energy transport, which enables a reasonable prediction of pressure build up by using CFD simulations. Still work is needed for more precise radiation spectra including the presence of admixtures from contacts and nozzle material. The admixtures of such polymer and metal vapors regarding distribution, composition and its influence on radiation and interruption capability need further research. For predictions of the interruption performance a better understanding of the phenomena around current zero and the post current zero phase is needed. This needs research on thermal and chemical non-equilibrium and arc induced turbulence, taking into account the coupling of these processes. For the dielectric recovery sufficiently precise breakdown models and validations are needed. Due to the 3D nature of many processes 3D modelling will be increasingly used in the future. The work for identification of alternatives to SF_6 is ongoing and needs to be continued with sufficient effort.

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