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RESEARCH ON DISCHARGE CHARACTERISTICS IN ULTRA-HIGH PRESSURE GASES (SUPERCRITICAL FLUIDS): A BRIEF REVIEW

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Abstract. This paper provides a review of the research on discharge characteristics in ultra high pressure gases (supercritical fluids) and discusses different applications in various fields. Followed by a summary on the investigations performed on the application of supercritical fluids for power switching purposes. A brief overview of the open research questions related to characterization of ultra high pressure switching arcs concludes the paper.

Keywords: ultra high pressure, supercritical fluid, arc discharge, current interruption.

1. Introduction

Increased operating pressure of gas based switching devices has been an effective way to enhance their current interruption capability. This becomes even more important if there are some restrictions on the type of the gases eligible to be used in power system equipment, e.g. because of the adverse environmental impact of fluorinated greenhouse gases.

With increase of the gas pressure, many of the thermodynamic and transport coefficients of the gas, relevant for its dielectric insulation behavior and arc extinction performance will change. One of the most obvious changes is the increase in gas density. It is well known that the density of the insulation medium is in direct correlation with its dielectric breakdown strength [1, 2], and therefore the gas at an elevated pressure is expected to have a much higher dielectric breakdown strength.

A further pressure increase may lead to a phase transition from gas state to liquid state in many materials. Such a liquefaction is considered undesired in high voltage applications as an eventual gas condensation results in lower gas densities available as insulation medium. In some materials, however, under certain circumstances, another phase called as the supercritical phase may form. The supercritical fluids are understood as fluids at very high density (comparable to that of liquids) enjoying the superior gas properties like lower viscosity without having some undesired characteristics of insulating liquids such as bubble formation by heating.

Based on this background, supercritical fluid would be an ideal candidate when it comes to dielectric insulation properties. This has been the main motivation for many studies (see for example [3–5]) to investigate the dielectric breakdown characteristics of different supercritical fluids including carbon dioxide (CO_2) and nitrogen (N_2) under different voltage stresses.

Besides gas density increase, some other thermodynamic and transport coefficients of the gas relevant for the heat transfer experience significant changes. In many experimental investigations, an anomaly near the critical point of the gases, i.e. the temperature and pressure combination where a transition from the gas state to supercritical state happens, is observed leading to very large thermal conductivity of fluid, and significant increase in the specific heat capacity of the fluid [6–8]. Such an enhanced heat transfer would be beneficial for the current interruption if these observations can be extended to the temperature and pressure regions relevant for switching arcs.

This has been the motivation to investigate the applicability of supercritical fluids for current interruption purposes. As the transition from gas to supercritical state occurs at very high pressures, some limitations related to design of test objects and execution of experimental measurements involving switching arc, especially at high energies or high currents exist. Therefore, the experimental results relevant for current interruption are scarce; some are related to pulsed power application [9–11], where the supercritical fluid is used in a sort of plasma closing switch with almost no current interruption capability but fast dielectric recovery, enabling repetitive switching in a pulse power system. The only series of experiments [12–18] , which are to some extent relevant for switching applications in power grids, performed by one of the research groups, in ultra high pressure nitrogen for maximum current amplitudes of few hundred amperes.

Another set of investigations on characteristics of arc discharges in very high pressure gases aimed at their application in gas discharge lamps [19, 20], where DC arc discharges with currents up to 100 A in Argon at pressures up to 10 MPa have been studied. Although this application field is completely different compared to power switching, and not the same material types have been investigated, there could be some synergies when it comes to the arc characteristics.

In this paper, an overview of the investigations on different aspects of application of supercritical fluids in high voltage switching equipment is presented and

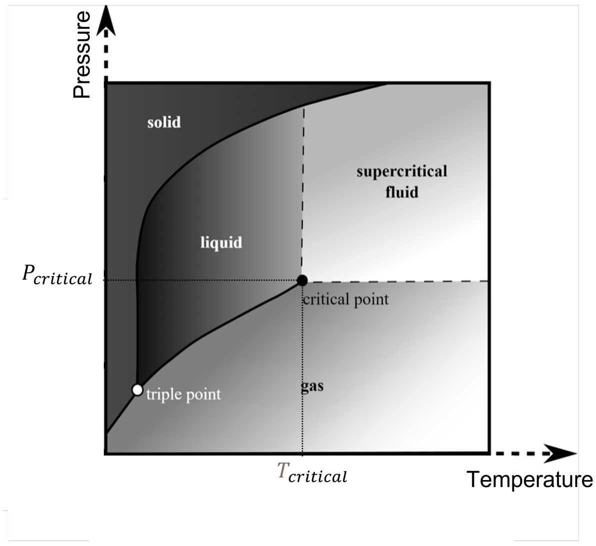

Figure 1. A typical phase diagram showing the transition to the supercritical fluid.

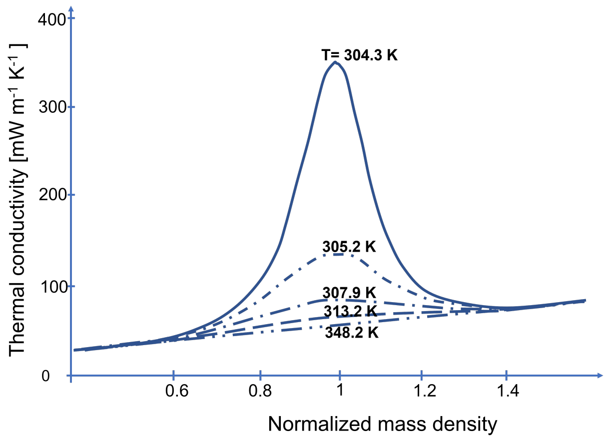

Figure 2. Anomaly in thermal conductivity of CO_2 near its critical point. Normalized mass density in this graph is the ratio of the mass density to the critical density. The schematics is inspired by [6, 8] and experimental results of [7].

the potential necessary research for characterization of discharges in supercritical fluids relevant for such applications is briefly outlined.

2. Supercritical fluids

For some gases or gas mixtures, if the pressure and temperature exceed a critical pressure (P_{critical}) and a critical temperature (T_{critical}), the so-called supercritical fluid will form as shown schematically in a simplified phase diagram in figure 1. The density of a supercritical fluid is comparable to that of liquids while its viscosity is more like gases. There would be no bubbling in case the supercritical fluid is heated, and it possesses high thermal conductivity, high specific heat capacity and high diffusivity.

The critical pressures and temperatures for some selected gas types are listed in table 1. As seen, the transition to the supercritical fluid happens at very high pressures exceeding the normal operating pressure of high voltage equipment, which could bring complexity in design of apparatus and also in experimental investigations, as will be further elaborated in the next chapters.

The supercritical fluids have, however, attracted some interest in the power switching community recently and they have been used in several other application fields. Supercritical CO_2 has found applications in in chemical (food) processing technology, e.g. fluid extraction [21] where it is used as a highly efficient solvent, or in supercritical fluid based turbines [22] where the combination of high density and low viscosity of supercritical fluids have been used to realize more compact turbines with higher efficiencies.

Besides high density, low viscosity and high diffusivity of supercritical fluids, they were investigated many decades ago by the material scientists when studying their characteristics near the critical point. A singularity in thermal conductivity and specific heat capacity of different materials near their critical point have been reported by different research groups, indicating superior heat transfer near critical point for the supercritical fluids. Figure 2 shows schematically the increased thermal conductivity of CO_2 near its critical point. All temperatures are above the critical temperature, and the combination of mass density and temperatures indicate that the material is in the supercritical state, but the pronounced increase in thermal conductivity is observed just near the critical point.

Moreover, the plasma in supercritical fluids have found several application fields in chemical synthesis and material processing, e.g. for nanomaterials synthesis [23], and is considered as one of the promising research fields relevant for low temperature plasma application in a recent plasma roadmap [24]. There have been also some exploratory investigations towards application of supercritical fluids for power switching purposes, as mentioned earlier.

3. Breakdown in high density gases and supercritical fluids

Dielectric breakdown in an insulation system is a statistical phenomenon related to initiation of enough number of charged particles (mostly electrons). Depending on the form of applied voltage stress (or the field-time action), different phenomena may play a role. If the static breakdown is concerned, the effective impact ionization is dominant which is mainly dependent on the mean free path of the electrons. An increase in the pressure of an insulating gas results in higher densities, and as shown in figure 3, the density seems to be a key parameter for the static electric strength [2]. More relevant parameters are the ionization energy, electrode geometry, pressure and temperature (particle number density). In the

Material	$P_{critical}$ (MPa)	$T_{critical}$ (K)	Critical density (Kg / m^3)
CO_2	7.38	304.1	469
N_2	3.35	126	314
H_2O	22.06	647.1	322
C_2H_6	4.87	305.3	203

Table 1. Critical pressure, temperature and density for some selected materials.

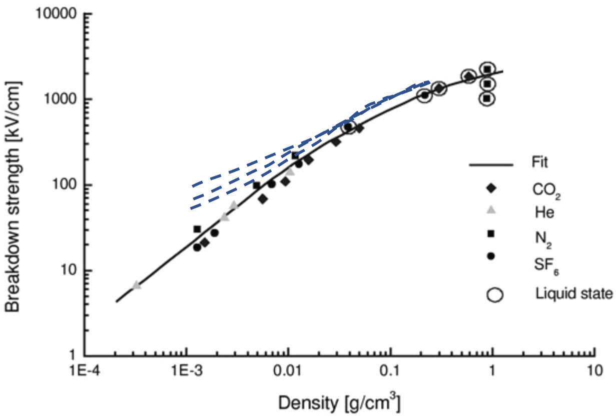

Figure 3. Static breakdown strength of different gases and liquids versus density [2] the dashed lines are from [1] for CO_2 at different gap lengths.

transition between different phases, no pronounced change in dielectric breakdown strength is observed. This finding may be extended to the transition from gaseous to supercritical fluid.

Several other studies have investigated the breakdown phenomena at very high densities under different voltage forms. One of the most relevant voltage forms for power system applications is the so-called impulse voltage, which should replicate the situation where the power equipment is exposed to lightning overvoltages. Dielectric breakdown in supercritical CO_2 exposed to standard lightning impulse with a rise time in the range of µs has been studied [25]. In [3], different gases including synthetic air, CO_2, a mixture of CO_2 and O_2 as well as CF_4, in the pressure range 0.5 to 10 MPa were exposed to a rather slow impulse voltage with a rise time of 130 µs. Two important observations made: no pronounced change in breakdown behavior by the transition to the supercritical fluid, and a saturation in electric strength at pressures higher than 2 MPa. The temperature is not given explicitly and therefore it is not unambiguously possible to find the densities, but the breakdown voltages are lower compared to the static breakdown of figure 3. The saturation of dielectric breakdown strength was also reported in [26] for nitrogen at a pressure of 1.7 MPa.

In some other studies, the pulsed breakdown behavior of different supercritical fluids for different gap lengths and electrode geometries has been investigated. It seems that the supercritical fluids can withstand very large dielectric strengths of several hundreds of kV/mm in nitrogen [4, 27] as well as in CO_2 [5, 28, 29], where the largest breakdown voltages reported for very small gap lengths [5].

In a series of papers [30–32], dielectric breakdown behavior of supercritical fluids and fluid mixtures including CO_2 [30], $CO_2 - C_2H_6$ [31] and $CO_2 - CF_3I$ [32] near their critical point at a short gap length of 0.1 mm has been studied. An interesting observation has been that an abrupt increase of dielectric breakdown by the transition from gas to supercritical phase occurs. It is, however, not exceeding the breakdown voltages of the liquid phase. It was linked to the abrupt density increase of the fluid near the critical point, and it is shown that this correlated to the density fluctuations near the critical point caused by cluster formations in the supercritical phase. The authors could measure breakdown fields as high as 200 – 300 kV/mm.

Even though the applied voltage shape, electrode geometry and gap lengths and materials are different in the above mentioned studies, the same conclusion can be drawn, namely that the dielectric breakdown remains even for supercritical fluids in direct correlation to the density, and therefore no breakdown voltages above the liquid levels with comparable densities can be expected.

4. Discharges in supercritical fluids

4.1. Pulsed discharges

As already mentioned, discharges (plasmas) in supercritical fluid have been used for different applications. In many applications related to chemical synthesis and material processing, pulsed discharges are employed. These could be low temperature plasma, e.g. caused by barrier discharge in supercritical fluids, or high temperature plasma caused by breakdown in plasma closing switches using supercritical fluids, which have been proposed for repetitive switching of high voltage high current pulsed power systems. The pulsed discharges are nanoseconds to microseconds discharges, and in many cases in short gap lengths of micrometer to hundreds of micrometer (the so-called microdischarges or microplasmas [23]) in contrast to the (several) millisecond switching arcs usually found in power switching devices in the power grids. Therefore, this type of discharges are considered of little relevance for the switching arc characteristics when interrupting large currents in power networks. Estimations made in [28] indicate that the discharges in supercritical fluid reach the local thermodynamic equilibrium in a very short time of 1 ps to 1 ns, so that all pulsed discharges in supercritical fluids can also be considered as thermal arcs; the arc core temperatures are comparable to those estimated for high energy discharges (see e.g. [14]) and increase with the density of the insulating medium. The dielectric recovery to some 80 percent of the cold dielectric breakdown strength occurs almost instantaneously (after 1 µs) which is not in line with the observations made for high energy discharges at the same current levels.

4.2. High energy discharges

Two different sets of investigations have been performed on high energy arcs in ultrahigh pressure gases: many results are found for some gases relevant for high intensity gas discharge lamps like Argon. In this application, there is no focus on current interruption and the arc radiation properties are used for light generation.

The other sets of experiments, performed on ultrahigh pressure nitrogen exploring its applicability for current interruption purposes. The details of these experiments can be found in a series of earlier publications [12–18]. Different gas flow conditions, namely free burning arcs, arcs in tubular non-ablating nozzles (geometrically constricted arcs), arcs in ablating nozzles with different heating volume geometries (self-blast switch), arcs with forced gas flow (puffer switch), in a pressure range of 0.1 to 8 MPa at different current amplitudes, current frequencies exposed to different transient recovery voltage stresses are tested, see table 2.

Major findings of these studies are compiled together:

- The arc voltage is found to be dependent on the gas pressure, where an increasing arc voltage with gas pressure (which corresponds to an increased arc dissipation at higher pressures) is observed for all different flow conditions.

- Based on the arc radius and arc temperature estimations, the arc becomes more constricted with higher core temperatures when the gas pressure is increased.

- The thermal re-ignition seems to be very critical for the switching arcs in ultra high pressure media. Depending on the blow conditions, a mixed picture exists; for geometrical constricted arcs burning inside a tube as well those equipped with a heating volume to create some self-blast effect, a pressure increase from atmospheric pressure to 2 MPa results in worsening of thermal interruption capability, while a further increase to 4 MPa leads to significant current interruption capability. In contrast, for the actively blown arcs (puffer arrangement), the increase of pressure to 2 MPa and beyond resulted in steadily decreasing current interruption performance. It must be noted that in the puffer arrangement, the same spring energy is used, and because of differences in viscosities and densities at different pressures, the piston movement and the resulting puffer overpressure have not been the same.

- It takes tens to hundreds of microseconds for the switching gaps at different pressures in different configurations to recover. The slowest recovery has been as expected for the free burning arc, but surprisingly the recovery in self blast arrangement occurs faster compared to the puffer arrangement, where the dielectric recovery of the atmospheric conditions and ultra high pressure at 4 MPa show no significant difference, and both are much faster than that at 2 MPa.

It is well known that the product of density and specific heat capacity is a key parameter for thermal interruption capability, as near current zero the turbulent thermal conductivity dominates [33]. Ideally, this parameter should be very small for those temperatures where the electric conductivity is high (i.e. ionization started) and large for the arc sheath region where the temperatures are in the range of few kK. It would be interesting to evaluate the ultra high pressure gases from this point of view, but unfortunately not much data is available on the transport coefficients of gases of interest for switching devices at very high pressures for a wide range of temperatures.

Based on available thermodynamic and transport coefficients, e.g. for Argon, Xenon and Krypton [34] as well as for CO_2 [35] and Air [36], a pressure increase causes a shift of the first peak of the specific heat capacity towards higher temperatures. Density normally scales with the pressure, and therefore the product of density and specific heat capacity will have peak at higher temperatures when the pressure is increased. The start of electric conductivity increase is, however, also shifted to higher temperatures, so that it is not obvious that for all gases and pressures, a further gas pressure increase would automatically lead to a more favorable situation for current interruption. With other words, it is imaginable to have some optimum high pressures depending on the type of the gases, or even some pressure ranges where the current interruption performance is very low, if only the product of density and specific heat capacity is of concern.

5. Remarks on application of supercritical fluids in power system equipment

The available experimental results are too few to allow for a definitive conclusion on suitability of supercritical fluids for power switching purposes, but according to the results available, it seems that the higher arc dissipation at higher pressures could be utilized with an appropriate design to generate efficient gas flow conditions near current zero. A better tailored self blast design for higher pressures may be explored through simulations utilizing the thermodynamic and transport coefficients of the candidate gases over a wide range of temperatures and pressures. An interested

	free burning arc	**geometrically constricted arc**	**self blast switch**	**puffer switch**
current amplitude (A)	150 / 275 /425	150 /275 / 425	130 / 275 / 425	275 / 425 / 146 - 436
current frequency (Hz)	350 / 950	350 / 950	190 / 950	950 / 50
Rate of Rise of Recovery Voltage (V/µs)	9.8 - 85	9.8 - 85	9.8 - 85	39 - 81

Table 2. Summary of different experimental investigations on ultra high pressure switching arc in nitrogen.

reader may wonder why experimental investigations on high energy discharges in ultrahigh pressure gases are quite limited in number and in arc current amplitudes. The main reason is the complexity of design of very high pressure vessels capable of withstanding large pressure increases (in many cases also shock waves). It must be mentioned that the mechanical design criteria force keeping the volume of the ultra high pressure vessels as small as possible. This means dissipating a large amount of energy (e.g. when arcing at very high currents for long times of several tens of milliseconds) could lead to an uncontrollable dynamic pressure increase and an eventual catastrophic failure. This situation is to some extent comparable to the pressure rise during an internal arc fault in a switchgear before the pressure relief flaps (or rupture plates) open. It must be noted that the amount of dissipated energy in a high-pressure chamber during current interruption experiments (even at the short circuit current level) does not exceed few tens of kJ and is therefore not comparable to the dissipated energy of long burning arcs of few MJ in case of internal arc faults. The volume of a high-pressure chamber is, however, orders of magnitude smaller than that of a typical switchgear, so that a significant pressure increase can be resulted. Estimation of the actual pressure increase is quite complex, as the fraction of the dissipated energy that goes into the pressure increase of the gas depends on the volume and geometry of the chamber, type of the gas and electrode materials, and most likely on the filling pressure, and most investigations so far have focused on the filling pressures typical of switchgear [37]. In addition, for arc initiation in many of ultra high pressure experiments, an exploding wire is utilized because realization of feedthroughs (in particular mechanical) into the high pressure vessels is cumbersome. It has been shown that an exploding wire creates large pressure shock waves [38], which expose even higher stresses on the high pressure enclosure.

The same problematic will exist if a power switching equipment is designed for ultrahigh pressure conditions. Therefore, in general the incentive to go towards ultrahigh pressures or supercritical fluids would be very little, unless the necessary pressure is provided because of operating conditions of the equipment; one example could be subsea power switching devices, where the available pressure may be used in a smart way to keep the medium in power switching at the ultrahigh pressures, and in this way the pressure compensation schemes of the subsea equipment could be eventually simplified resulting in cost-efficient solutions.

In hybrid switching devices, short gap length disconnecting or current commutating switches utilizing supercritical fluids could be used if the arc duration and energy can be kept as low as possible. In such a design the superior dielectric strength of supercritical fluids would be then in of preliminary interest. An example of a hybrid DC switch with a fast opening disconnecting (or current commutating) switch in supercritical fluid is introduced in [39].

6. Conclusions

The question of applicability of ultra high pressure gases or supercritical fluids in high voltage equipment of power networks has been addressed in this paper. Two main aspects, namely the high voltage insulation or breakdown behavior, and the current interruption performance have been briefly evaluated based on previous investigations.

The results indicate an increasing dielectric strength with increased pressure (or density) of the dielectric medium, but the rate of increase is less pronounced for ultra high densities. So, using ultra high pressure gases or supercritical fluids would positively impact the high voltage insulation of a device. However, it is important that the marginal improvements are balanced against the increasing complexity of high voltage devices, particularly with the larger volumes.

The results on arc interruption capability of designs employing supercritical fluids are scarce, and only few experimental results for nitrogen are available. The available data show however no unambiguous improvement of current interruption performance for pressures exceeding the critical pressure compared to atmospheric pressure. Furthermore, a considerable worsening of current interruption capability was observed for an ultra high pressure region around 2 MPa for some of the designs. To be able to make a definitive conclusion on suitability of supercritical fluids for current interruption, further studies are necessary. Besides derivation of transport coefficients of the gas or gas mixture types of interest for a wide temperature and pressure range including the supercritical state, and tailored design of switches at ultra high pressures based on arc simulations, a first step towards design of high pressure vessels for more relevant (higher current) interruption tests would be to explore the current dependent pressure increase in enclosed chambers at ultra high filling pressures.

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