Transient discharges in technology: from electricity networks to plasma medicine

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Streamers, leaders, sparks and arcs are common phenomena in thunderstorms, and equally in plasma and high voltage technology. Within the talk I will review recent research directions in these application fields that are relevant or inspiring for thunderstorm researchers.

1. Evolution of pulsed discharges

1.1. The general dynamical mechanisms

When a high electric voltage is suddenly applied to lowly ionized media, the breakdown follows a sequence of physical mechanisms.

Uniform or streamer breakdown: First, depending on (i) the local electron density or the electron detachment processes from negative ions, and on (ii) the local electric field values, electric breakdown will occur in a more uniform manner [1], e.g., in the form of an inception cloud around some electrode [2], or in the form of streamers. Streamers will always be the mode of primary breakdown in fields below the breakdown value (where attachment and recombination are stronger than impact ionization), because they can propagate only by enhancing the electric field at their tips to values above breakdown. (For a generalization to the non-attaching atmospheres of Jupiter and Saturn, see [3].) At the streamer tips electrons can reach high energies and even enter the *run-away regime*. This is particularly the case for negative streamers that propagate in the same direction as the electrons. Streamers can form complex trees with hundred thousands of channels, as visualized in recent measurements of meter long discharges [4,5]. Streamer trees are modelled for 30 years by so-called dielectric break-down models [6,7]. A recent extension of such models with consistent charge transport can be found in [8].

Heating: As the created ionization is only transient, the electron density will decrease eventually due to attachment or recombination, if it is not maintained either by sufficiently high electric fields or by heating. Heat can be supplied by the excitations and decompositions of molecules in the discharge itself after thermal equilibration [9]. For short discharges, heating determines the spark formation after the discharge has crossed the gap in a streamer-like mode, while in long gaps the streamer-to-leader transition determines the growth mode of the discharge, as can be seen in [3,4]. Heating has two effects: first it decreases the gas density N and increases the reduced electric field E/N (that determines the ionization efficiency), and second it excites the molecules, up to thermal break-up in the arc or return stroke phase.

Plasma fluid interaction: The arc has its name from its form, and the form is created by the thermal rise of the hot air of the arc channel. It is one example of the interaction of discharge and gas dynamics where the low gas density guides the discharge, while the discharge has made the gas expand. Discharges can also be guided by gas composition, as they propagate easier, e.g., in He than in air. Surprisingly, the discharge can also guide the He flow in air through space charge effects [10].

Chemistry is initiated in the streamer ionization front under strongly non-equilibrium conditions, and continues throughout the discharge and in the afterglow.

1.2. Particular materials for applications

Air is the most relevant medium in geophysics. It is particular in two respects: free electrons are lost rapidly due attachment to oxygen, and there is a strong nonlocal photo-ionization mechanism in nitrogen oxygen mixtures that helps the steady propagation of positive streamers against the electron drift direction. Positive streamers, e.g., in *high purity nitrogen* propagate much more erratically, but persist longer [11]. How the electron persistence depends on the gas composition, has recently been investigated experimentally and theoretically in [12].

In noble gases discharges propagate even easier, as there are less inelastic processes leading to electron energy losses: no vibrations or rotations and only a limited number of electronically excited states. Positive discharges in Argon are as erratic as in nitrogen, but the transition to spark is even easier [11].

SF_6: The opposite effect occurs in SF_6, a standard gas for insulation and switching in high voltage technology. It has many internal degrees of freedom, and it attaches electrons so rapidly that researchers assume that there are no streamers at all, but that discharge propagation directly requires heating and the leader mechanism at standard temperature and pressure [13]. SF_6 is a very strong greenhouse gas, and it creates toxic products during discharges. Therefore replacements are now searched for.

An easy way to increase break-down strength is *to increase density*. Presently there are studies whether SF_6 could be replaced (at least in fractions) by CO_2 or N_2 at higher pressure. In particular, one of the authors is involved in studies of discharges in supercritical nitrogen [14] at up to 100 bar.

However, discharge mechanisms at (almost) *liquid densities* are not well understood. E.g., direct field ionization can become important in solids as a replacement of impact ionization, and recently the Zener mechanism of solid state physics has been applied to transformer oil [15] and to supercritical nitrogen [16]. However, how to transfer the Zener mechanism precisely from solid state lattices to fluids is not quite investigated. In any case, a direct field ionization mechanism does not require free electrons for streamer growth, and it would be interesting to further compare these different streamer growth mechanisms due to impact ionization or field ionization in the future.

Discharges in and near liquids are now studied in a dedicated EU-COST action [17].

2. Application areas

Application areas are numerous. The authors are particularly interested in the following major fields:

2.1. Gas chemistry, nanosecond pulsed discharges

Streamer corona discharges in air are used for more than 150 years to create O_3 which in turn is used for disinfection [18,19]. Corona reactors can break up organic molecules and hence bad odour, treat biofuels, surfaces etc. The O* radicals in the early stage of the discharge are even more efficient than O_3, but form O_3 rapidly.

Recent research has shown that the faster the voltage rises and decreases the more electric energy is converted into fast electrons and then into O* radicals [20]: electrons are accelerated to high energies while the gas stays cold. Electrical engineers are now in a race to create powerful electric circuits for nanosecond pulses and shorter.

2.2. Plasma medicine and plasma jets

A particular interest is presently in so-called plasma jets. These are so-called guided streamers propagating in a plastic tube filled with a noble gas. Electron energies are high in such media. Where the gas flow exits the tube, the energetic electrons hit air molecules and create molecular excitations and (V)UV radiation. These species are explored for wound and cancer treatment.

Plasma medicine has its own EU-COST action [21], special issues and even an own journal [22].

2.3 Plasma actuators for aviation and wind turbines

Plasmas can stir the air through several mechanisms [23]: momentum transfer from electric fields to charged species, and expansion due to discharge heating, or even electrostatic repulsion between streamers that changes the gas flow [10], see end of section 1.1. Plasma actuators inducing gas motion are currently being developed for aircraft and wind turbines, as a surface discharge at the front edge of a wing can keep the air flow over the foil laminar under extreme conditions [24, 25]. Plasma flow interaction is now also considered as a replacement of mechanical fans and blowers [26].

2.4 Plasma assisted ignition and combustion

Plasma assisted combustion builds on the combination of chemical and gas flow effects [23,27,28]. The plasma might break up oxygen molecules into O* radicals which allows combustion of leaner mixtures. At the same time the plasma induced gas motion helps mixing the fuel air mixture.

2.5 Electrical switches

Electric switches first replace a metal contact by an arc discharge and then extinguish the arc. This is how they interrupt, e.g., the current of a power plant, if need be. To remove the arc, both heat and conductivity need to be removed. DC electricity nets have lower energetic losses over long distances than 50 Hz nets and are presently under development both in China and in Germany to connect regions with sustainable energy sources with industrialized regions. DC switches are particularly challenging as the electric current never passes through zero.

Studies on arc formation and extinction in SF_6, or in supercritical N_2 or CO_2 for electric switches were already mentioned above, see also [29].

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