STREAMER TO SPARK TRANSITION IN SUPERCRITICAL N_2

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Abstract: We model the streamer to spark transition in supercritical nitrogen as this is a promising medium for electrical switching. We assume that the streamer has bridged the gap and that a weakly ionized channel with a constant field has formed. We model how the discharge energy is transferred from kinetic energy of electrons into particular molecular excitations and further into gas heating, and how the thermal expansion of the discharge channel sets in.

Keywords: Supercritical switch, gas heating, breakdown in supercritical N2, streamer to spark transition

Introduction

Sparks occur in many branches in nature and have a huge potential for technical applications in electrical switching of high power. Supercritical (SC) nitrogen is a very attractive medium to study, as it has high breakdown strength due to high density and, unlike liquids, doesn't form bubbles. In figure 1 we show the phase diagram of nitrogen, where the threshold values for the supercritical state are a temperature of T_c=126 K and a pressure of P_c=3.4 MPa. The goal of our research is to investigate dielectric recovery properties of SC nitrogen as a possible replacement of SF_6 in high voltage circuit breakers (CBs). Similar as in many other media, electric breakdown in SC nitrogen proceeds in three phases: first an avalanche and streamer phase where an initial ionization builds up, supported by space charge effects, then the transition of the deposited energy into heat during the streamer-to-spark transition, and then the spark phase, when thermodynamic and transport processes at any point are functions of temperature, pressure and of the degree of ionization.

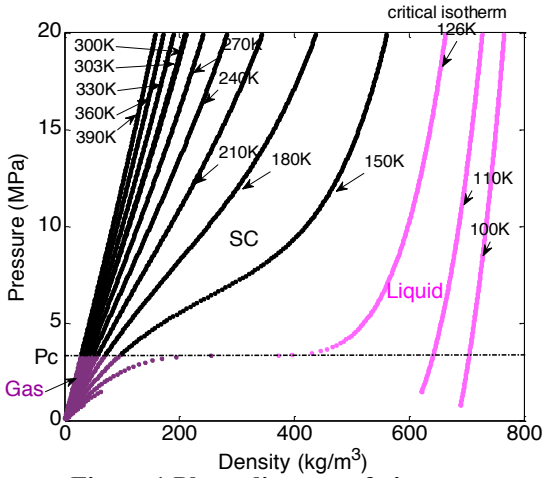

Figure 1 Phase diagram of nitrogen

In the present work we investigate the streamer to spark transition and estimate the induced thermal shock. Also we calculate space and time resolved profiles of macroscopic parameters of the SC nitrogen, e.g. temperature, density, pressure, etc. We assume that the applied electric field E is uniform in the axial direction [1, 2] and that we hence can employ a 1D axisymmetric model in radial direction as proposed in [3] for air.

Model Formulation

We employ the model proposed in [3] for air and use it to study the streamer to spark transition in SC nitrogen. The SC nitrogen initially has a pressure of 8 MPa, a temperature of 290 K and therefore a density of 94.5 kg m^{-3}. We assume that a streamer already has crossed the gap and has left an electron density of $n_e(r) = n_e(0)e^{-r^2/r_s^2}$ behind, with a channel radius of 50 μm and a maximal electron density of $n_e(0) = 3.6e22\ \mathrm{m}^{-3}$; this defines the initial condition of our calculation.

In the sequel we will assume that the process stays homogeneous in the axial direction, and we will only study the evolution in the radial direction. We assume the electric field E to take a constant value of 4 MV/cm.

The conductivity is dominated by the electron density and given by $q\mu n_e(r)$, where μ is the electron mobility, assumed to depend on the reduced electrical field E/N (N is the number density of SC nitrogen) and calculated with BOLSIG+ [4] and q is the elementary charge.

The dynamics of the SC nitrogen as a medium is described by the balance equations of mass, momentum and energy and for the vibrational energy of nitrogen [3, 5, 6], as the transition from vibrational into thermal energy is slow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial r} = 0 \qquad (1)$$

$$\frac{d(\rho u)}{dt} + \frac{\partial(\rho u^2 + P)}{\partial r} = 0 \qquad (2)$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial[(\varepsilon + P)u]}{\partial r} = \eta_T Q_e + Q_{VT} \qquad (3)$$

$$\frac{\partial \varepsilon_V}{\partial t} + \frac{\partial(\varepsilon_V u)}{\partial r} = \eta_V Q_e - Q_{VT}, \qquad (4)$$

Here $\rho, u, P, \varepsilon, \varepsilon_v$ represent respectively the mass density, velocity, pressure, energy density (per unit volume) and vibrational energy density of nitrogen.

$Q_e=\sigma_e \cdot E^2$ is electronic Joule energy deposition rate per unit volume. The Q_{VT} term describes the transfer of energy from vibrational energy levels of nitrogen to the translational energy level (for more detailed description see [3]). The energy density is defined as $\varepsilon = 1/2\rho u^2 + P/(\gamma - 1)$, where γ=1.55 is the specific heat ratio C_P / C_V is kept constant in the model.

During the initial discharge phase, electrons are accelerated in the electric field and deposit their energies by impact in different degrees of freedom of the nitrogen molecules; these can be translational, rotational or vibrational states of the molecules and electronic excitations or ionization. As the concept of temperature implies that the available energy is distributed equally over all degrees of freedom of the gas, a temperature is not defined initially. Rather one has to track the mean energy within the different excited states. In particular, the vibrational states of the molecules have a long relaxation time τ_{VT} [7] for thermalization. Therefore, we treat the energy of the vibrational states separately and assume that 30% of the fraction of electronic η_{ele} contributes to direct gas heating [1, 7, 11]. However the energy fraction in vibrational level η_v doesn't contribute gas heating directly, but is translated into mainly rotational level through a time named as

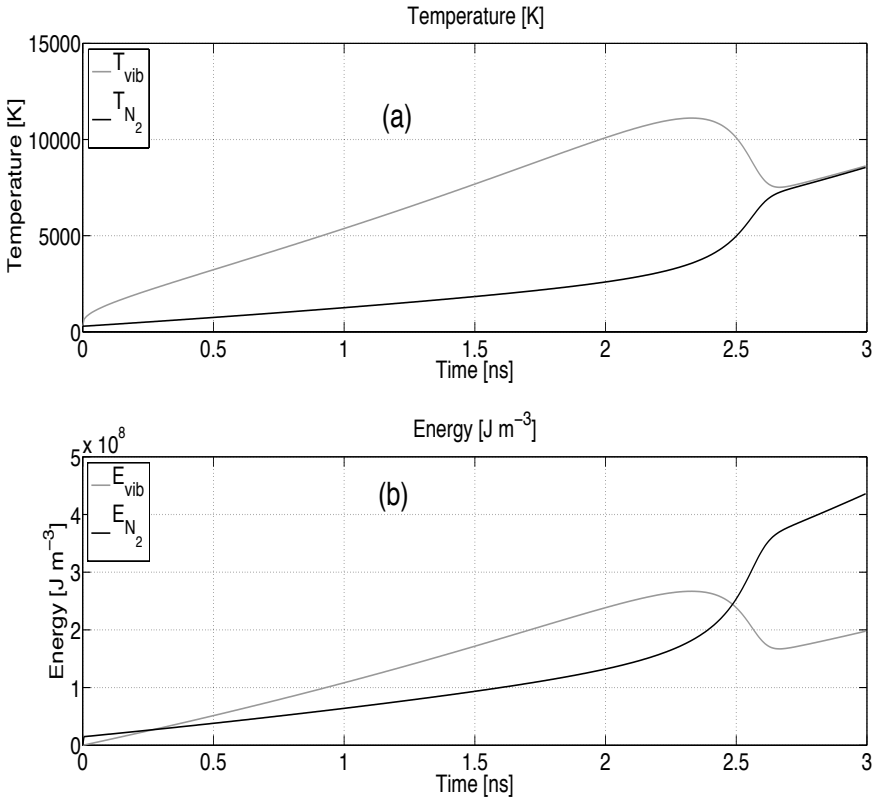

Figure 2 Temporal dynamics of (a) vibrational and gas temperatures, (b) vibrational and translational (gas) energies.

relaxation time of vibrational to translational energy level, denoted as τ_{VT}. So, we can write term η_T as fraction of energy directly contributes to gas heating $\eta_T = \eta_{tr} + \eta_r + 0.3\eta_{ele}$, and fraction that takes time to be relaxed into gas heating $\eta_V = \eta_v$. The threshold energy for difference levels and the corresponding energy loss fractions are got from BOLSIG+ software [4], with defined reduced electrical field E/N, and nitrogen temperature T_g.

In the kinetic scheme calculating electron density n_e, we consider electron impact ionization and electron-ion attachment. Euler system is coupled with kinetic scheme to describe the time dynamics of the density of electrons and the positive ions [1, 2]. The reaction rates are obtained from [10].

The Euler system (1)-(4) is discretized using a second order non-staggered, semi-discrete NT scheme [8] for the space derivatives and a third-order SSP Runge-Kutta solver [9] for the time derivatives. All source terms and kinetic equations are treated explicitly. As time integration is explicit, the time step δt should be limited to value of $\min(\delta r/c, \tau_{VT})$, where δr is a space step, $c = \sqrt{\gamma P/\rho}$ is the sound velocity in the SC nitrogen and Q_{VT} is the timescale describing the relaxation of the energy of the vibrationally excited nitrogen molecules into the translational energy.

Results

In this section we discuss the results obtained from our simulations. Figure 2 shows temporal dynamics of vibrational and neutral nitrogen temperature during 3ns from the start. Both temperatures are rising almost linearly until ~ 2.4 ns. After 2.4 ns, the vibrational temperature drops exponentially from 11000 K to 7000 K within a 0.3 ns. Oppositely, the gas temperature rises exponentially from 3000 K to 7000 K. After 2.7 ns, vibrational temperature and neutral nitrogen temperature rise linearly. From reports of laboratory experiments, it is found that the streamer to spark transition time has the relationship with gas density $\tau_s \propto 1/N$ [3]. According to the results of our model, τ_s=2.4 ns confines with this relationship. Similar behaviour has been observed in STP air [1, 2, 3], where vibrational and neutral nitrogen temperatures reach the value of 5000 K in 0.95 μs [3].

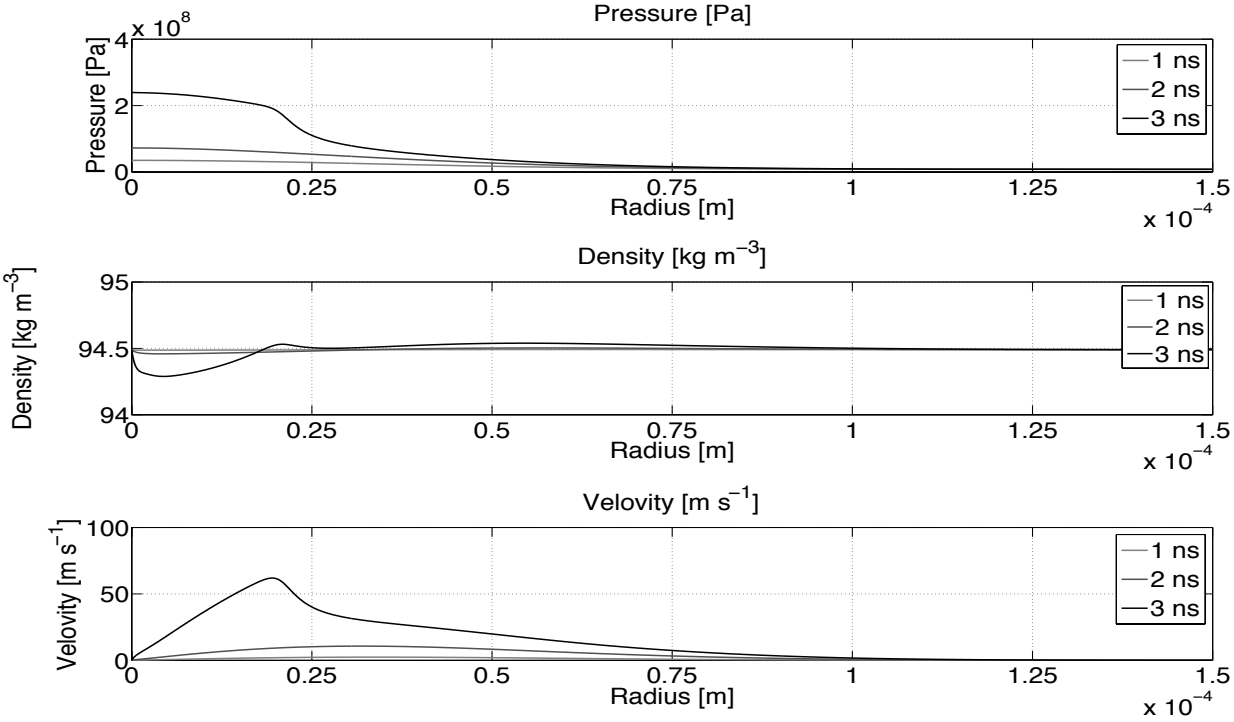

Figure 3. Pressure, density and velocity as a function of the radial coordinate at 1 ns, 2 ns and 3 ns.

Figure 4 shows distributions of pressure, density and velocity as a function of the radial coordinate at 1 ns, 2 ns and 3 ns. Within the first 3 ns since streamer bridging the electrodes, pressure inside

the channel increases more than 2 times; nitrogen molecular move towards the outer edge of spark channel, with a peak value of velocity locates at 24 μm from the radial axis at 3 ns; simultaneously the density of SC nitrogen decreases at position before the velocity peak and increases behind it. All these quantities further away from the channel remain unchanged during 3 ns time. Figure 4 is in very good agreement with Figure 3. During the first 2 ns, when the nitrogen temperature and the vibrational temperatures are increasing linearly, pressure, velocity and density are not varying significantly. After 2ns, when the gas temperature rises exponentially we observe dramatic changes in the channel for the parameters such as pressure, velocity and density.

Conclusions

In present work we generate a model of streamer to spark transition inside SC nitrogen, based on the model proposed by [3]. The time domain of this model is 3 ns from streamer bridging the electrodes. The neutral nitrogen temperature increases to value 7000 K and merges with vibrational temperature at 2.4 ns, thus, thermo equilibrium phase of the spark reaches. From the results of modelling we find the streamer to spark transition time is about 2.4 ns, which has good agreement with the relation $\tau_s \propto 1/N$. The parameters of nitrogen inside the spark channel such as pressure, density and velocity doesn't vary much within 2 ns after the initial moment, while the most significant changes happen in time region 2 ns - 3 ns. This work gives a clear impression about the streamer to spark transition inside SC nitrogen. Based on the results of our work, further theoretical studies of electrical discharges inside SC fluid can be preceded.

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