Finite Element Method Plasma Simulation of Nitrogen Contaminated Metal Halide Lamps

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Abstract: The ceramic metal halide lamps belong to the most efficient high intensity light sources of these days. Presently it is the nitrogen contamination that causes the most significant problems during ignition. If this material gets into the lamp's interior in high concentrations, it will make the lamp unable to ignite properly at lower voltages.

In this work, a two-dimensional plasma transport model was used in order to reveal the principal changes and effects that can be caused by nitrogen contamination during the process of breakdown. The final goal is to determine the critical nitrogen concentration that makes the lamps dysfunctional.

A self-consistent fluid model was developed in Comsol Multiphysics® Plasma Module for studying the discharge phenomena. The model gives a complete description of spatial- and time evolution of the discharge plasma. Amongst others, the chemical reactions were one of the key features that were investigated to identify the reactions that generate the most important changes in the ignition of the lamp.

The results show that the nitrogen dissociation reaction affects the electrons' kinetic energy distribution mainly by electron energy dissipation. Taking every result into consideration the critical nitrogen concentration is around 500 ppm. Higher concentrations than this create significant change in those parameters of the lamp that are decisive during the breakdown process. In this case the breakdown voltage has to be increased in order to make the lamp possible to ignite.

Keywords: CMH, lamp, nitrogen, contamination

1. Introduction

Different gas mixtures affect the parameters of the ceramic metal halide lamps different ways (eg. breakdown voltage, luminosity, color-rendering). While some of these – in appropriate concentrations – help the operation of the lamp, other mixtures impede it. The nitrogen belongs to the latter group as it allows electron-impact reactions that shifts the electron-energy distribution needed for the breakdown toward the lower energy regime. This effect makes the ionization reactions unlikely.

Since the nitrogen contamination causes the major problem, the final goal is to understand the nitrogen induced effects and changes during the transient processes of breakdown, and to determine the critical nitrogen concentration that changes the processes and the operation of the lamp significantly.

2. Experimental Setup

The lamp's geometry was created according to the plan of the 70 W lamp produced by General Electric Lighting. The distance of the electrodes is 7.4 mm. As the lamp is axisymmetric, a two-dimensional axisymmetric model was made (figure 1).

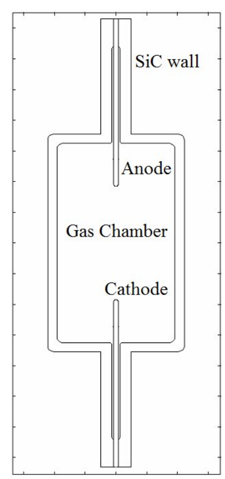

Figure 1. Structure of the lamp

During the examination of breakdown only that part of the lamp is relevant which contains the plasma, so just the lamp's gas chamber was involved in the model. The environment was modeled with a bigger sphere around the lamp.

The model of the electrical circuit consists of two parts. The ideal voltage source is connected to one of the electrodes through an integrating part that consists of a resistor and a capacitor. The second electrode is connected it through an electric ballast (figure 2).

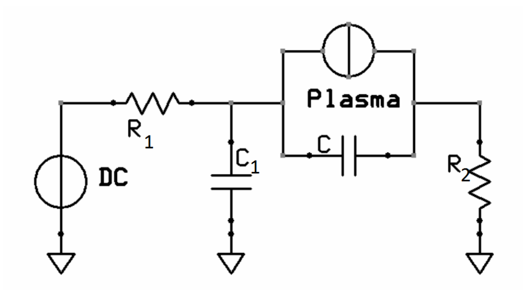

Figure 2. Circuit diagram of the lamps's electrical circuit

The time constant of the voltage is determined by the C_1 capacitor and the R_1 resistor. The electric ballast is symbolized by the R_2 resistor. The plasma physical processes are coupled with the electrical circuit through the current source and the C capacitor. The voltage between the electrodes and the voltage of the C capacitor are identical, and the current between the electrodes (which is determined by the plasma physical processes) is generated by the current source in the electrical circuit. The parameters of the circuit:

- U_{DC} = 800 V
- R_1 = 5000 Ω
- C_1 = 10^{-10} F
- R_2 = 10000 Ω

In addition to the nitrogen contamination, there was argon in the gas chamber, as this is the gas that plays the key role during the process of breakdown. The temperature of the gas was 300 K, and the pressure was set to $3 \cdot 10^4$ Pa. The material of the gas chamber's walls was silicon-carbide and there was air in the environment. The physical parameters of the materials were set to the default values contained in the database of COMSOL Multiphysics.

3. Use of COMSOL Multiphysics

3.1 Finite Element Mesh

Aside from boundary layers triangular mesh was used in the model. Near the electrodes, where the remarkable gradient of the intensive quantities induce determinative physical processes, finer mesh was used. The effects of the solid surfaces necessitate the usage of boundary layers. The mesh is shown on figure 3. The colours indicate the quality of the mesh: red parts are parts with rougher mesh, while the blue parts show regions where extremely fine mesh was applied.

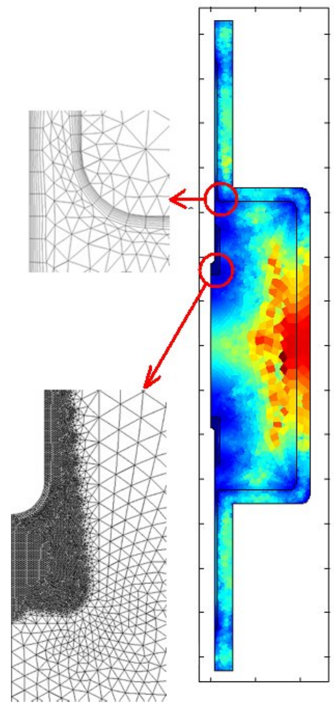

Figure 3. Mesh of the lamp

3.2 Modeled Particles

The model contains only the main energy levels of the numerous existing states of particles, because these are sufficient for understanding the most important processes, and the others does not influence the results significantly. [1] The energy levels of the nitrogen molecules, the possible reactions and the forward reaction kinetic constants were set according to [2], and we set the reactions and the energy levels of argon according to [3]. The modeled particles are shown in table 1.

Table 1: Modeled particles

Sign	Name	Energy
e^-	electron	
Ar	argon – ground	0.00 eV
Ar^*	argon – excited	11.55 eV
Ar^+	argon – ionized	15.76 eV
N	atomic nitrogen – ground	0.00 eV
N^*	atomic nitrogen – excited	7.10 eV
N^+	atomic nitrogen – ionized	15.66 eV
N_2	molecular nitrogen – ground	0.00 eV
N_2^{*A}	molecular nitrogen – excited	7.10 eV
N_2^{*B}	molecular nitrogen – excited	7.80 eV
N_2^{*C}	molecular nitrogen – excited	11.30 eV
N_2^+	molecular nitrogen – ionized	15.70 eV

The *denotes the excited states, the A, B, C letters symbolize the nitrogen molecule's three different excited energy levels. The energy levels are shown on figure 4.

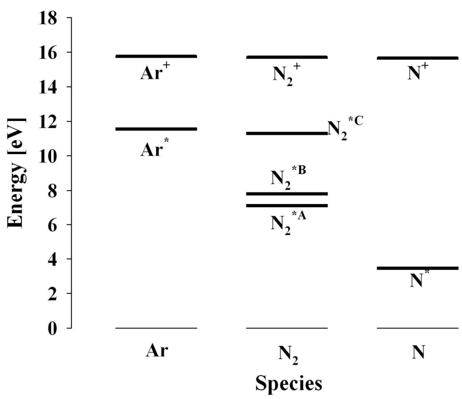

Figure 4. Energy levels of the modeled particles

3.3 Reactions

The plasma physical reactions were set according to [2], [3] and [4]. The involved electron-impact reactions:

$$
\begin{aligned}
e^- + Ar &\rightarrow e^- + Ar \\
e^- + Ar &\rightarrow e^- + Ar^* \\
e^- + Ar^* &\rightarrow e^- + Ar \\
e^- + Ar &\rightarrow 2e^- + Ar^+ \\
e^- + Ar^* &\rightarrow 2e^- + Ar^+ \\
e^- + N_2 &\rightarrow e^- + 2N \\
e^- + N_2 &\rightarrow 2e^- + N_2{}^+ \\
e^- + N_2 &\rightarrow 2e^- + N + N^+ \\
e^- + N_2 &\rightarrow e^- + N + N^* \\
e^- + N_2 &\rightarrow e^- + N_2{}^{*A}
\end{aligned}
$$

The involved reactions between the heavy species:

$$
\begin{aligned}
Ar^* + Ar^* &\rightarrow e^- + Ar + Ar^+ \\
Ar + Ar^* &\rightarrow Ar + Ar \\
N_2 + N &\rightarrow N_2^{*A} + N \\
N_2^{*A} + N_2^{*A} &\rightarrow N_2 + N_2^{*B} \\
N_2^{*A} + N_2^{*A} &\rightarrow N_2 + N_2^{*C} \\
N_2 + N_2^{*A} &\rightarrow N_2 + N_2 \\
N + N_2^{*A} &\rightarrow N + N_2 \\
N_2 + N_2^{*B} &\rightarrow N_2 + N_2 \\
N + N + N_2 &\rightarrow N_2 + N_2^{*B} \\
Ar^+ + N_2 &\rightarrow Ar + N_2^+ \\
Ar^* + N_2 &\rightarrow Ar + N_2^{*B} \\
Ar^* + N_2 &\rightarrow Ar + N_2^{*C} \\
Ar^* + N_2 &\rightarrow Ar + N + N \\
Ar + N + N &\rightarrow Ar + N_2^{*B} \\
Ar + N_2^{*B} &\rightarrow Ar + N_2
\end{aligned}
$$

In addition to the reactions written above, there are other types of reactions with the solid surfaces. In general one can say that the excited or ionized particles get into the ground state while interacting with the surfaces. Furthermore, the small, fast moving argon ions can generate secondary electrons when colliding with the electrodes.

4. Discussion

4.1 Ignition Times

The breakdown process was examined with different nitrogen concentrations. That moment was considered as the instant of breakdown, when the current reached 10 mA on both electrodes. The voltage generator of the electric circuit model produced 800 V in all cases, and the initial electron concentration was 10^{10} 1/m^3. Figure 5 shows the moment of breakdown of two differently contaminated lamps.

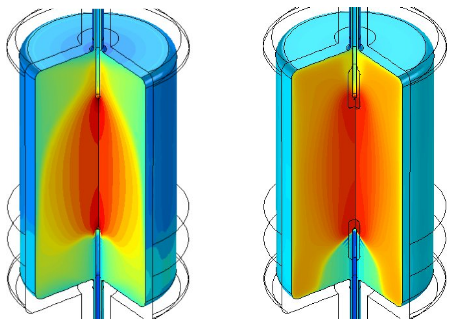

Figure 5. Electron concentration at the moment of breakdown

One can see, that the higher the nitrogen concentration, the wider the conduction channel is: the distribution of electron density spatially extends. If the effect of the RC part of the electrical circuit is neglected, the current determines the voltage between the electrodes. This means that the impedance of the lamp is determined at a given current, so it is independent of the gas chamber's material. This implies that the wider conduction channel means a higher value of resistivity.

Table 2 shows the times of breakdown at different nitrogen concentrations.

Table 2: Time of breakdown

Contamination	Time of breakdown
0 ppm	4.18 µs
100 ppm	4.20 µs
400 ppm	5.60 µs
1600 ppm	17.80 µs
3200 ppm	57.40 µs
6400 ppm	189.20 µs

Figure 6 illustrates these data.

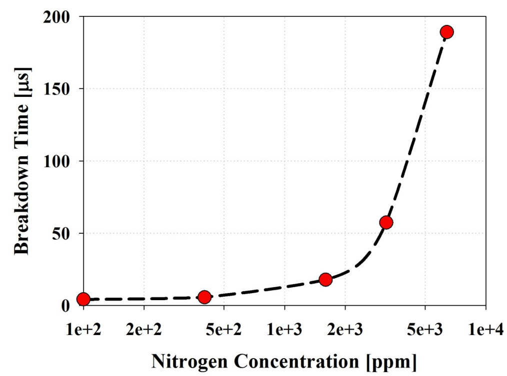

Figure 6. Time of breakdown as the function of nitrogen concentration

As the concentration of nitrogen increases, the time needed for the breakdown increases as well. The energy of the electrons is consumed without the generation of new charge carriers. This means that there is more energy needed for the generation of the same amount of charge carriers if the nitrogen concentration is higher. Figure 7 illustrates the energy needed for the production of 1 C free charge as the function of nitrogen concentration.

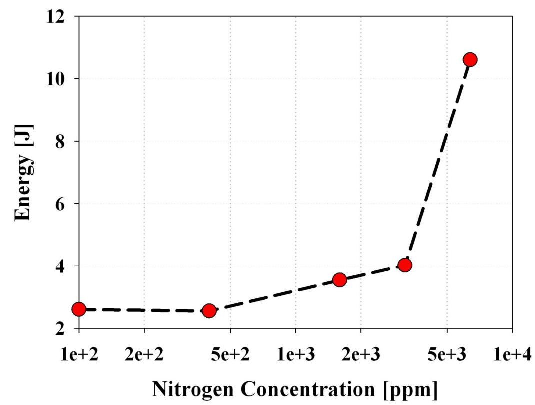

Figure 7. Necessary energy for 1C free electron

4.2 Energy Balance

As the nitrogen concentration becomes more significant, the ratio of energy expended on the ionization gets lower. Figure 8 illustrates the energy consumed by the three most important reaction types.

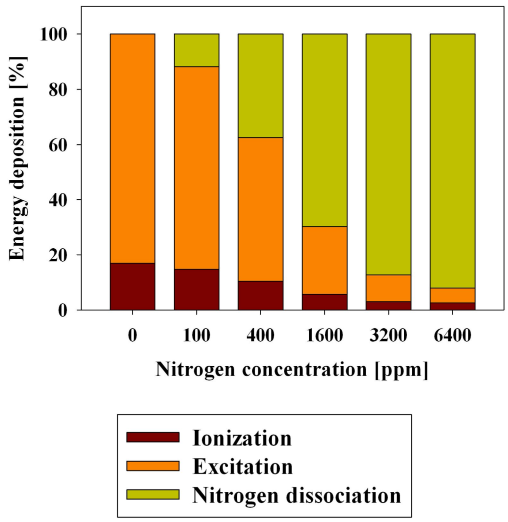

Figure 8. Energy consumed by the different reaction types

The ratio was calculated until the moment of breakdown. The reactions were divided to three categories: excitation, ionization and nitrogen dissociation. While the ratio of excitation and ionization remains roughly the same, the dissociation reactions consumes more and more energy as the nitrogen concentration increases. The model contains three dissociation reactions, but two of them are negligible compared to the

$$e^- + N_2 \rightarrow e^- + 2N$$

reaction. The reason for this is the reaction's kinetic constant. Figure 9 illustrates the kinetic constants of the electron-nitrogen reactions.

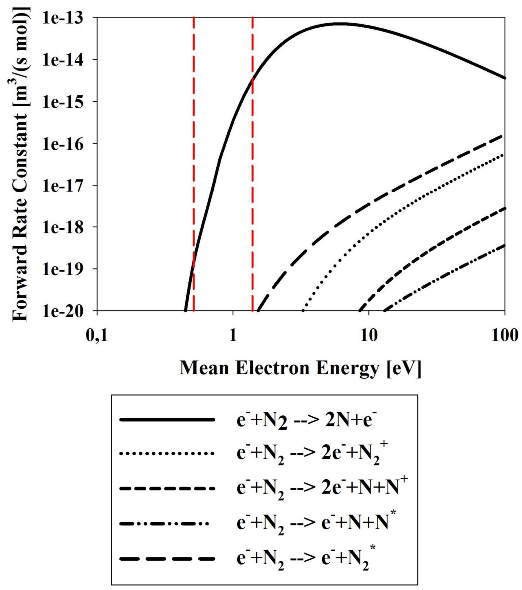

Figure 9. Electron—nitrogen reactions' reaction kinetic constants

The two dashed lines indicate the energy interval where the mean energy of the electrons' varies until the moment of ignition. The cross section of the above mentioned reaction exceeds by orders of magnitude the others' in this energy regime. Consequently, the energy is consumed by this reaction that does not facilitate the process ignition with new charge carriers.

5. Conclusion

All in all the nitrogen hinders the emergence of breakdown, because of the high cross section of

$$e^- + N_2 + 9.8407eV \rightarrow e^- + 2N$$

nitrogen dissociation reaction. This reaction consumes the electrons' energy so that no new charge carrier is produced. The effect of this reaction is even more significant as it causes a remarkable loss of energy. [5] Above a nitrogen concentration of 500 ppm, more than half of the electrons' energy is lost because of the nitrogen dissociation reaction, so higher, than this concentration generates significant changes in the processes of the lamp.

This result draws attention to the fact, that nitrogen contamination has to be controlled carefully during the production of ceramic metal halide lamps.

6. References

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