Modelling mercury-free HID lamps: Breakdown characteristics and thermodynamics

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ABSTRACT

The modelling of mercury free HID lamps is challenging due to the complexity of gas mixtures and sensitivity of breakdown characteristics to the initial physical conditions. In this paper we report on results from a computational investigation of breakdown characteristics and the plasma properties of mercury-free HID lamps having metal halide fills. We discuss breakdown time as a function of voltage rise times, polarities and plasma composition (e.g., hot and cold restart). We also discuss the thermodynamic properties for doses containing Xe/NaI/ScI_3/ZnI_2. The simulator used in this work, *nonPDPSIM*, is a plasma hydrodynamics model in which continuity, momentum and energy equations are solved for charged species with solution of Poisson's equation. The model is coupled with a thermodynamics module providing local thermodynamic equilibrium (LTE) properties. Algorithms were developed to represent the transition of the lamp from a kinetics-Poisson regime during breakdown to an LTE-ambipolar regime as the arc begins to form.

BREAKDOWN CHARACTERISTICS

The breakdown process of HID lamps can be characterized by a statistical and a formative time lag. One mode of breakdown requires a high ignition voltage and is characterized by initial plasma formation in the volume of the lamp between the electrode tips. Another ignition mode is characterized by streamer propagating along the wall. In this case, the lamp breaks down at lower voltages.

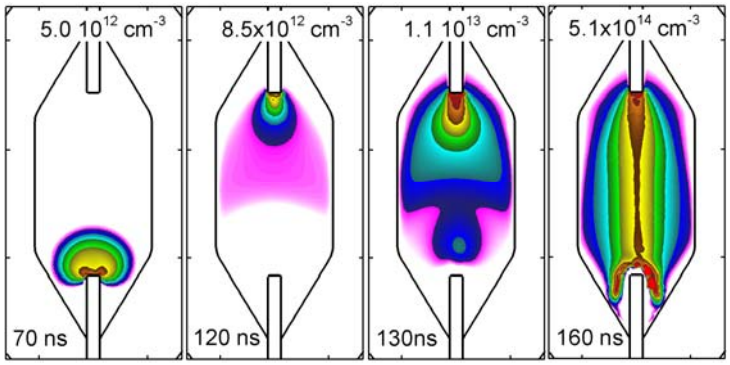

Figure 1. Electron density (3 dec) at 4 times. Negative polarity is applied to bottom electrode. The voltage rise time dV/dt=150 V/ns. Breakdown time lag is mainly determined by the time-of-flight of seed electrons.

Dosed HID lamps often have a condensed and mildly conductive salt layer on the interior of one side of the lamp. In the absence of the salt layer, the formative breakdown time is determined by the time-of-flight of seed electrons produced in the vicinity of the cathode. We studied the formative breakdown time-lag in a lamp of D4 geometry having a xenon gas fill of 8 atm by injecting electrons into the gap resulting from roughness enhanced field emission from the negative (relative to plasma) electrode. The D4 lamp is 2.7 mm in diameter with an electrode spacing of 4.2\ mm. After emission from the cathode, the electron cloud drifts towards the opposite electrode. Plasma parameters for a negative pulse with dV/dt=150 V/ns applied to the bottom electrode are shown in Figure 1. The total voltage span is 30 kV. Upon reaching the positive upper electrode, the cloud initiates a positive streamer toward the negative electrode. The positive streamer propagates downward towards the cathode where it meets the opposite negative streamer and breakdown occurs. For these conditions the cloud drifts in rapidly increasing electric field during the first 50 ns of flight (first and second frames). The breakdown then rapidly develops during the following 20-30 ns (second and third frames).

The existence of condensed salt layers on the inner wall of the HID lamp and on the electrodes influences the ignition behaviour of the lamp. For example, we found that streamers tend to propagate along the inner wall with the salt deposits. This is due to the conductive nature of the salt layers that focuses the electric fields produced by the electrodes. For example, the effect of a conductive salt layer on breakdown time is shown in Fig. 2. The operating conditions are as in Fig. 1. The salt layer has a thickness of a few microns with conductivity 10^{-3} Ω^{-1} cm^{-1}. The breakdown generally occurs more rapidly and asymmetrically. The effect is more pronounced when the salts are deposited as separate islands (as opposed to a uniform film) due to local field enhancement near the islands' edges.

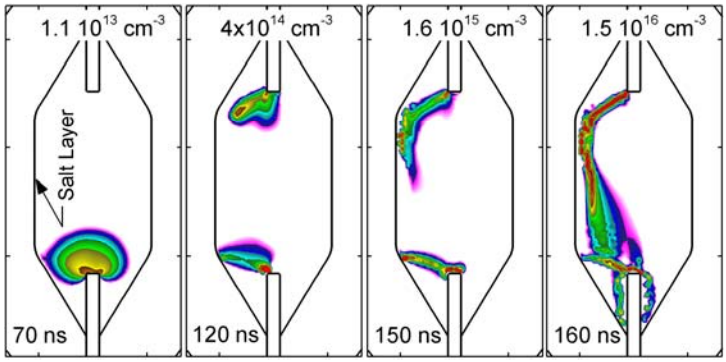

Figure 2. Effect of salt layer on breakdown time. Electron density (2 dec) is shown at 4 successive time moments Conditions as in figure1. Breakdown time lag is determined by time-of-flight of seed electrons as well as by faster development of streamer due to enhancement of electric filed by the salt layer.

THERMODYNAMICS

In mercury-free HID lamps, the mercury is often replaced by ZnI_2. This substitution, along with the use of conventional metal halides such as NaI and ScI_3, add both complexity and potential variability to the system. For example, it has been experimentally shown that the lamp operating voltage can be controlled by varying the amount of ZnI_2. To develop models of such lamps assuming LTE, knowledge of the thermodynamic properties of both dose substances and plasma composition are required. Calculation of the plasma composition does not necessarily use reaction rate constants when detailed balancing between direct and reverse reactions is used. Detailed energy balance modelling, however, requires data for enthalpy, entropy and heat capacitance of species [1]. For example, the LTE plasma composition for a D4 lamp is shown in Fig. 3 as a function of temperature. The fill of the lamp in relative mole fractions (gas phase) is $Xe/NaI/ScI_3/ZnI_2 = 1/3.16\times10^{-4}/4.63\times10^{-5}/4.48\times10^{-5}$. The effects of mixing, segregation and ionization of light and heavy additives on thermal, electrical conductivity and I-V characteristics will be discussed. The thermodynamic database constructed for these doses will be also discussed [1].

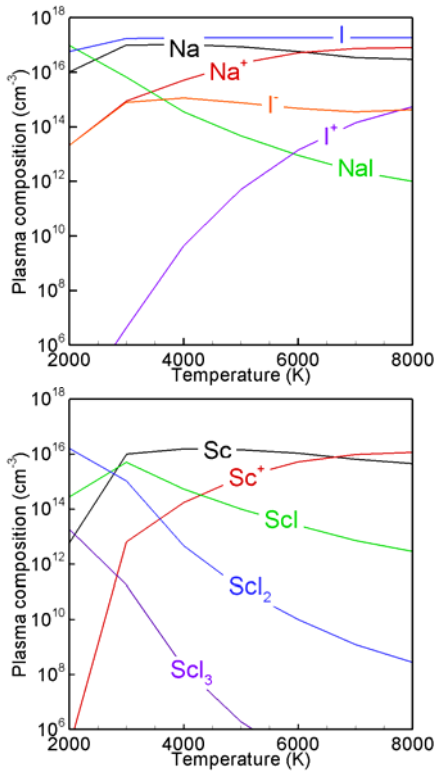

Figure 3. D4 ($Xe/NaI/ScI_3/ZnI_2$ fill) plasma composition vs temperature (a) NaI molecule and its dissociation fractions , (b) ScI_3 molecule and its dissociation fractions. Na is almost totally ionized at high temperatures, ionization of Sc occurs at higher temperatures.

REFERENCES

[1] M.W. Chase et. al., JANAF Thermochemical Tables. Fourth Edition. Part I and II. (1992).

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