Theoretical investigation of CMH lamps ignition properties in Ar/Hg gas mixtures

Sz. Beleznai*[1], I. Maros[2]
[1] Budapest University of Technology and Economics, Department of Atomic Physics, 1111 Budapest, Budafoki str. 8, Hungary,
[2] General Electric Lighting, GE Hungary KFT, Váci út 77, Budapest, H-1044, Hungary
*Corresponding author: 1111 Budapest, Budafoki str. 8, Hungary, Building FIII, beleznai@dept.phy.bme.hu

Abstract: Two-dimensional plasma transport model was developed in COMSOL Multiphysics Plasma Module to investigate fundamental issues in ceramic metal halide (CMH) lamps starting using Ar/Hg penning gas mixture. The intent of this work is to provide insight into possible design rules that might be applied to the improvement of start-up in moderate pressure metal halide lamps. The model gives a complete description of spatial- and time evolution of the discharge plasma. The overall characteristic derived from experimental data has been well described. The results indicate that the Penning effect has a strong influence on the breakdown voltage. At low Hg vapor pressure the results show significant voltage reduction at startup, while large partial pressures of mercury considerably deteriorate discharge ignition efficacy.

Keywords: plasma, discharge, metal halide lamp, ignition, reaction kinetics

1. Introduction

Metal halide lamps have gained more and more popularity because of their high efficiency and good colour rendering properties. It has already been reported that the breakdown voltage can be lowered in several ways from the level needed by pulse-ignited lamps [1].

In this work, results from experiment and a two-dimensional plasma transport model will be used to investigate fundamental issues in lamp starting using Ar/Hg penning gas mixture. The intent of this work is to provide insight into possible design rules that might be applied to the improvement of start-up in moderate pressure, metal halide lamps.

2. Experimental Setup

The investigated lamp is cylindrically symmetric about the centerline. The upper electrode is powered while the lower one is grounded. The ceramic tube confines the plasma. The quartz tube has a radius of 3.6 mm. The inter-electrode gap is fixed at 7.4 mm. In the experimental work breakdown voltage vs. lamp temperature were recorded. Lamp temperatures determine the vapor pressures of mercury.

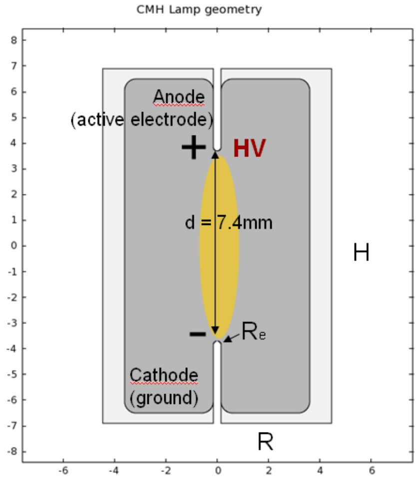

Figure 1. CMH lamp geometry

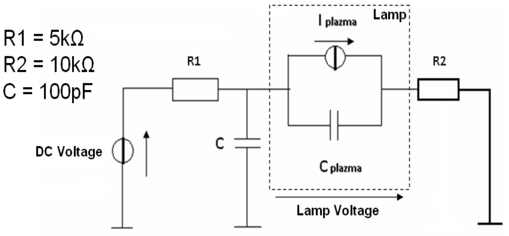

Figure 2. Electrical driving circuit

3. Use of COMSOL Multiphysics

A 2D 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 Ar, Hg plasma species, electron densities, mean electron energies, space and surface charge distributions. Electron energy distribution function (EEDF) is calculated by solving zero dimensional Boltzmann equation. Rate equation analysis over 30 reaction processes [1] between 8 atomic, ionic and molecular states of argon and mercury including electron-, heavy-body collisions are taken into account. The major physical quantities are monitored such as transport of particles and transport of momentum, generation and recombination, electron particle densities and electron energy densities; chemical reactions in the plasma. The conservation of particle- and energy-densities regarding electron density n_e, mean electron energy $\langle \varepsilon_e \rangle$ are calculated by:

I. Poisson equation

$$\Delta(\varepsilon_0 \varepsilon_r \Phi) = e(n_i - n_e)$$

II. Continuity equation

$$\Gamma_e = \mu_e E n_e - D_e \nabla n_e$$

$$\frac{\partial n_e}{\partial t} + \nabla \Gamma_e = S_e$$

III. Energy conservation

$$\Gamma_{We} = \frac{5}{3} \mu_e E n_e \langle \varepsilon_e \rangle - \frac{5}{3} D_i \nabla (n_e \langle \varepsilon_e \rangle)$$

$$\frac{\partial (n_e \langle \varepsilon_e \rangle)}{\partial t} + \nabla \Gamma_{We} = -e \cdot \Gamma_e \cdot E + S_{We}$$

where S_e represent the inter-particle collision source term for electrons. The fluxes of electrons Γ_e, and electron energy Γ_W are approximated by the drift-diffusion equations.

4. Discussion of the Results

One of the ways to induce breakdown at lower reduced electric field is to add a small admixture of a mercury to the lamp that operates with Ar as a starting gas. Excited Ar atoms can ionize ground state Hg atoms (Penning-effect), hereby producing significant number of free electrons. The Penning effect has a strong influence on the breakdown voltage, therefore this feature is often used to lower the breakdown voltage in CMH lamps. At low Hg vapor pressure (~350K), the results show significant voltage reduction at startup (Figure 3).

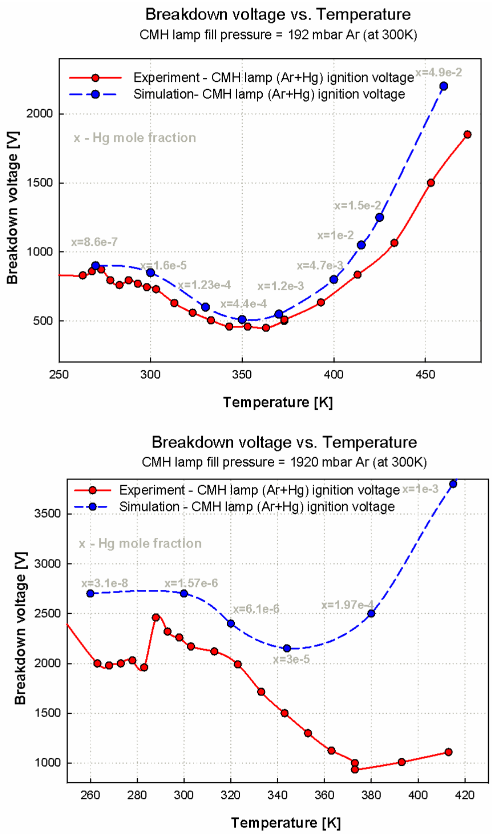

Figure 3. Experimental and simulation values of breakdown voltage at 192 mbar and 1920 bar Ar CMH lamps (at 300K). Hg vapor pressures are function of lamp pressures (see also Figure 4).

However beyond a certain limit (Hg mole fraction > 1e-3 at 192 mbar Ar pressure and > 1e-4 at 1920 mbar Ar pressure), Hg addition means a disadvantage for the system ignition efficacy. As Hg has a lower excitation and ionization potential than Ar, the magnitude of Hg excitation processes become significant and simultaneously direct ionization of Ar and Hg are kept at low rate. Penning effect can not compensate the loss of the decreased number charges produced in direct ionization processes. During hot operation of the lamp the increased Hg proportion makes the ignition process more difficult and increases the required the startup voltages of the lamp.

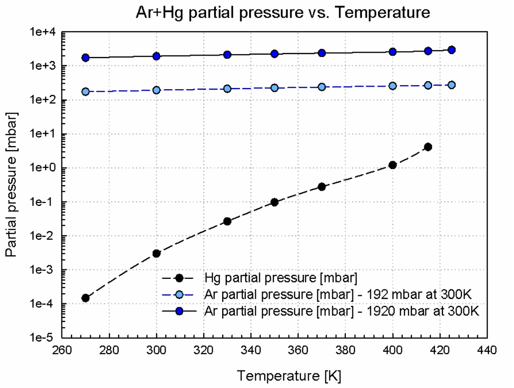

Figure 4. Ar and Hg partial pressures as a function of temperature

As Hg has a lower excitation and ionization potential than Ar, large fraction of Hg particles utilize most of the input electrical energy for excitation processes. As a consequence the rate of ionization processes are kept at low level. Therefore beyond a certain Hg limit (> 0.1 mbar), Hg addition means a disadvantage for the system startup capability (Figure 5, Figure 6).

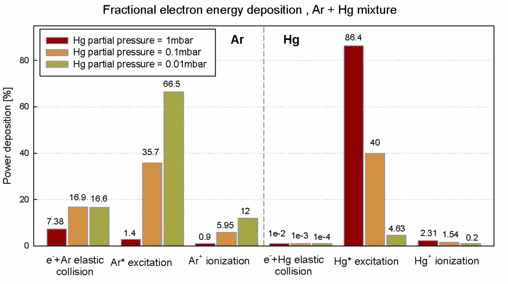

Figure 5. Fractional electron energy depositions

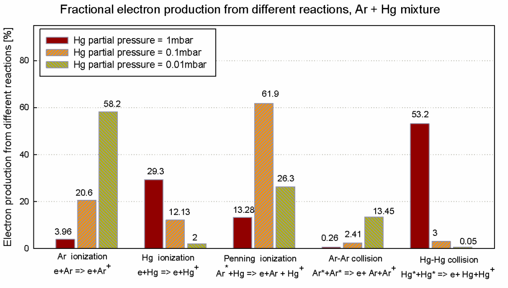

Figure 6. Fractional electron production from different reactions

5. Conclusions

Using small portion of Hg ($4.4*10^{-4}$ Hg mole fraction at 192 mbar gas pressure and $3*10^{-5}$ Hg mole fraction at 1920mbar gas pressure), the simulation results show significant voltage reduction at startup (between 20-40%). However beyond a certain Hg limit (Hg mole fraction > 10^{-3} at 192 mbar Ar pressure and > 10^{-4} at 1920 mbar Ar pressure), large Hg addition means a disadvantage for the system startup potential, as the magnitude of Hg excitation processes become significant. According to the author this unwanted effect happens at hot-restrike phenomena, therefore eliminating Hg from the system would be favorable in respect of decreasing breakdown voltages.

6. References

1. Brian Lay, Richard S Moss, Shahid Rauf and Mark J Kushner, Breakdown processes in metal halide lamps, *Plasma Sources Sci. Technol.* **12** 8–21 (2003)