Theoretical Investigation of CMH Lamps Ignition Properties in Ar/Hg Gas Mixtures

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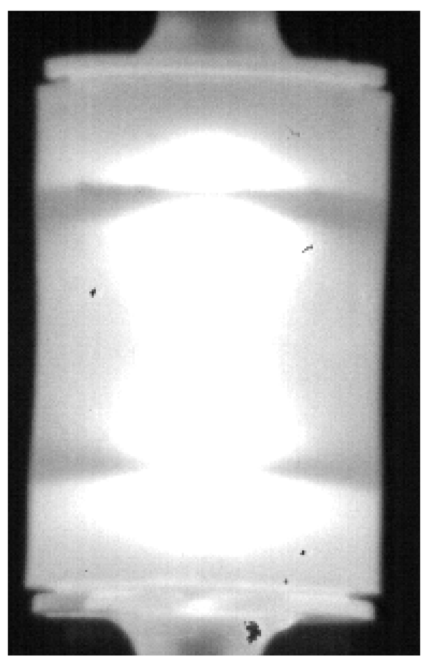
Introduction



Metal halide (MH) lamps typically have cold fills of tens to a few hundred Torr of a rare gas and the vapour from the dosing of a metal halide solid and mercury. Breakdown and starting of the lamp occurs following application of multi-kV pulses across electrodes separated by a few centimeters. **Improving the reliability and reducing the breakdown voltage for starting metal halide lamps is of great interest**. Large starting voltages result in higher rates of sputtering of the cathode which ultimately reduces the lifetime of the lamp. In this report, **possible voltage reduction options** aimed to help both cold start and warm restrike ignition properties **are investigated theoretically and experimentally**

Plasma simulation (COMSOL MULTIPHYSICS PLASMA MODULE®)

• 2D finite element fluid dynamical model, temporal and spatial evolution of the Ar, Hg plasma species, electron densities, mean electron energies, space and surface charge distributions by solving continuity equations

I. Poisson equation

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

II. Continuity equation

$$\frac{\partial n_e}{\partial t} + \nabla\Gamma_e = S_e \qquad \Gamma_e = \mu_e E n_e - D_e \nabla n_e$$

III. Energy conservation

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

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

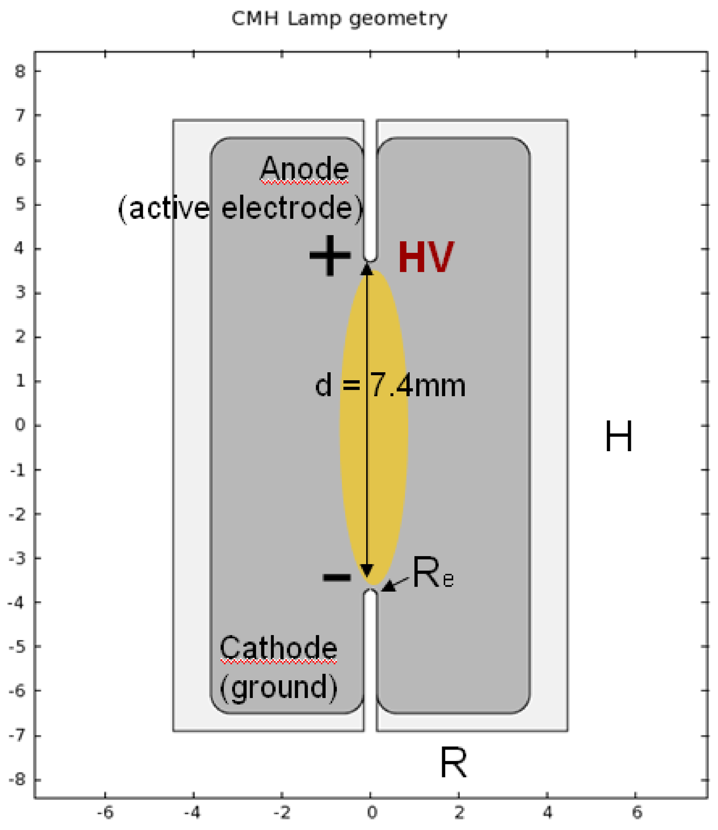
• Electron energy distribution function (EEDF) calculated by solving zero-dimensional Boltzmann equation

• Rate equation analysis over 30 reaction processes* between 8 atomic, ionic and molecular states of argon and mercury including electron-, heavy-body collisions

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

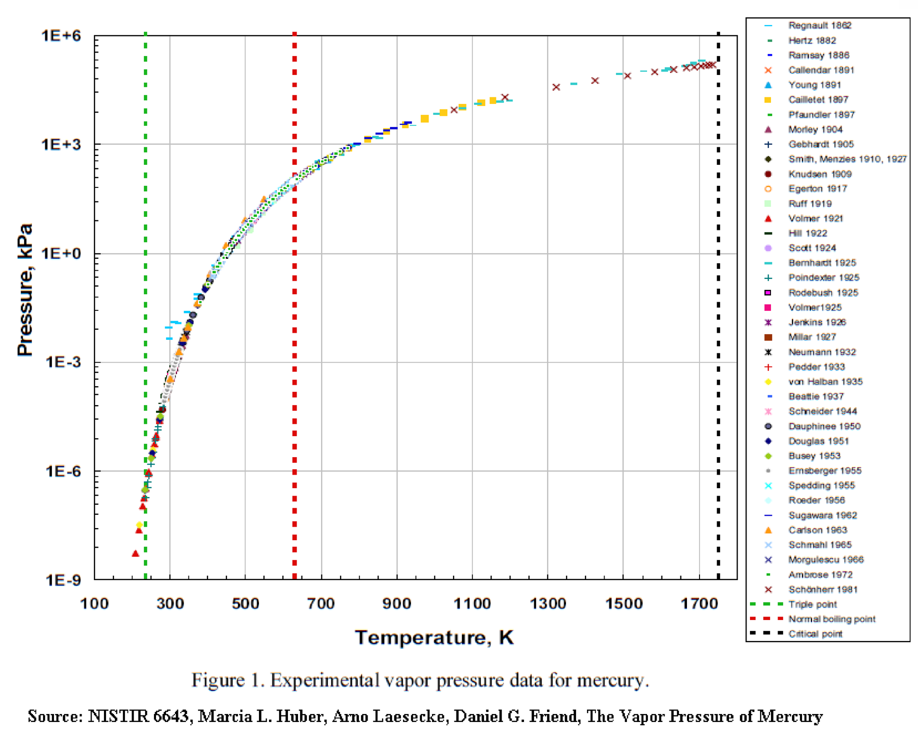
Argon gas partial pressure	100 – 2000mbar
Hg gas partial pressure	10^{-4} – 10^{1} mbar
Electrode distance	7.4 mm
Applied Voltage	500-3000 V
Ceramic tube radius	3.6 mm
Electrode radius	150 um

CMH Lamp geometry



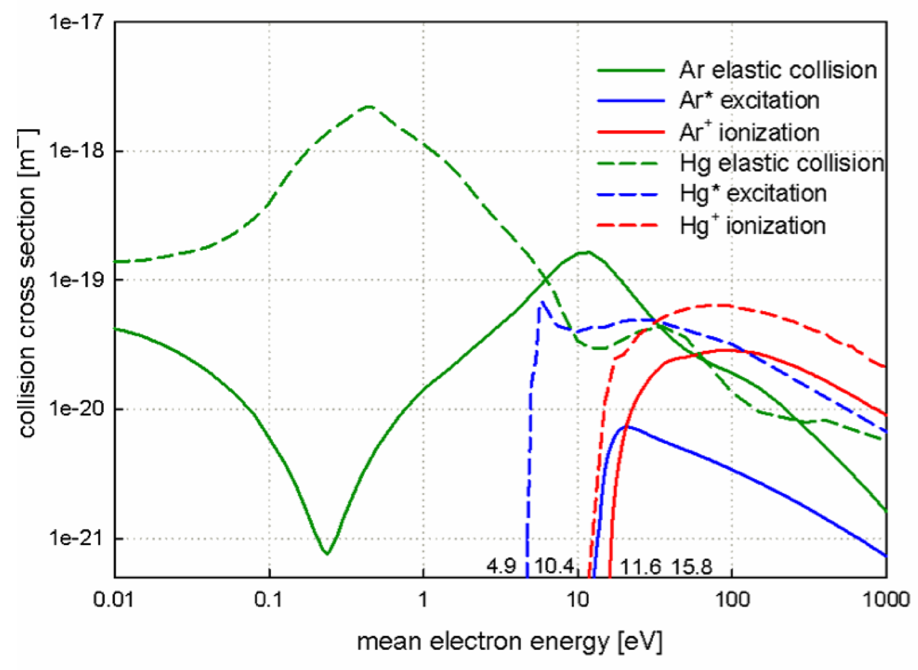
Reactions	Rate coefficient[a]
$e + Ar \rightarrow Ar + e$	EEDF
$e + Ar \rightarrow Ar^* + e$	EEDF
$e + Ar^* \rightarrow Ar + e$	EEDF
$e + Ar \rightarrow Ar^+ + e + e$	EEDF
$e + Ar^* \rightarrow Ar^+ + e + e$	EEDF
$e + Ar^+ \rightarrow Ar^*$	$4.0 \times 10^{-13} T_e^{-0.5}$
$e + e + Ar^+ \rightarrow Ar^* + e$	$5.0 \times 10^{-27} \times T_e^{-4.5}\ cm^6\ s^{-1}$
$e + Ar_2^* \rightarrow Ar_2^+ + e + e$	$9 \times 10^{-8} T_e^{0.7} \times \exp(-3.66/T_e)$
$e + Ar_2^+ \rightarrow Ar + Ar + e$	1×10^{-7}
$e + Ar_2^+ \rightarrow Ar^* + Ar$	$5.38 \times 10^{-8} T_e^{-0.66}$
$e + Hg \rightarrow Hg + e$	EEDF
$e + Hg \rightarrow Hg^* + e$	EEDF
$e + Hg^* \rightarrow Hg + e$	EEDF
$e + Hg \rightarrow Hg^+ + e + e$	EEDF
$e + Hg^* \rightarrow Hg^+ + e + e$	EEDF
$e + Hg^+ \rightarrow Hg^*$	$4.0 \times 10^{-13} T_e^{-0.5}$
$e + e + Hg^+ \rightarrow Hg^* + e$	$5.0 \times 10^{-27} \times T_e^{-4.5}\ cm^6\ s^{-1}$
$Ar^* + Ar^* \rightarrow Ar^+ + Ar + e$	5×10^{-10}
$Ar_2^* + Ar_2^* \rightarrow Ar_2^+ + Ar + Ar + e$	5×10^{-10}
$Ar^+ + Ar \rightarrow Ar + Ar^+$	4.6×10^{-10}
$Ar^* + Ar + Ar \rightarrow Ar_2^* + Ar$	$1.14 \times 10^{-32}\ cm^6\ s^{-1}$
$Ar^+ + Ar + Ar \rightarrow Ar_2^+ + Ar$	$2.5 \times 10^{-31}\ cm^6\ s^{-1}$
$Ar_2^* \rightarrow Ar + Ar$	$6.0 \times 10^{7}\ s^{-1}$
$Ar^* \rightarrow Ar$	$10\ s^{-1}$
$Ar^* + Hg \rightarrow Hg^+ + Ar + e$	5×10^{-10}
$Ar^* + Hg^* \rightarrow Hg^+ + Ar + e$	5×10^{-10} (Penning effect)
$Ar_2^* + Hg \rightarrow Hg^+ + Ar + Ar + e$	1×10^{-10} (Penning effect)
$Ar_2^* + Hg^* \rightarrow Hg^+ + Ar + Ar + e$	1×10^{-10}
$Ar^+ + Hg \rightarrow Hg^+ + Ar$	1.5×10^{-11}
$Ar^+ + Hg^* \rightarrow Hg^+ + Ar$	1.5×10^{-11}
$Ar_2^+ + Hg \rightarrow Hg^+ + Ar + Ar$	1×10^{-12}
$Ar_2^+ + Hg^* \rightarrow Hg^+ + Ar + Ar$	1×10^{-12}
$Hg^+ + Hg \rightarrow Hg + Hg^+$	1×10^{-9}
$Hg^* + Hg^* \rightarrow Hg^+ + Hg + e$	4×10^{-10}
$Hg^* \rightarrow Hg$	$1 \times 10^{6}\ s^{-1}$
$h\nu + Hg \rightarrow Hg^+ + e$	$5 \times 10^{-15}\ cm^2$
$M^+ \rightarrow wall \rightarrow M$	
$M^* \rightarrow wall \rightarrow M$	

•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. Lamp temperatures controlled to determine the vapor pressures of mercury.



Experimental vapor pressure for mercury

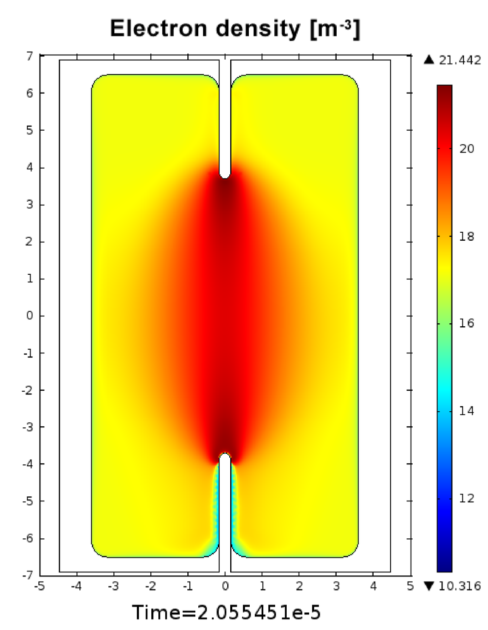
Electron collision cross section for Ar/Hg gas

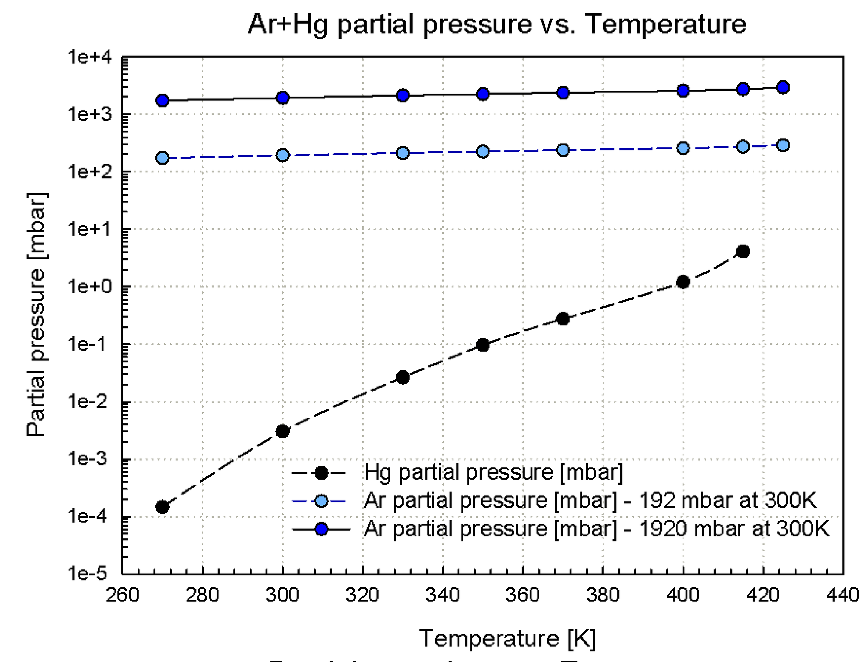


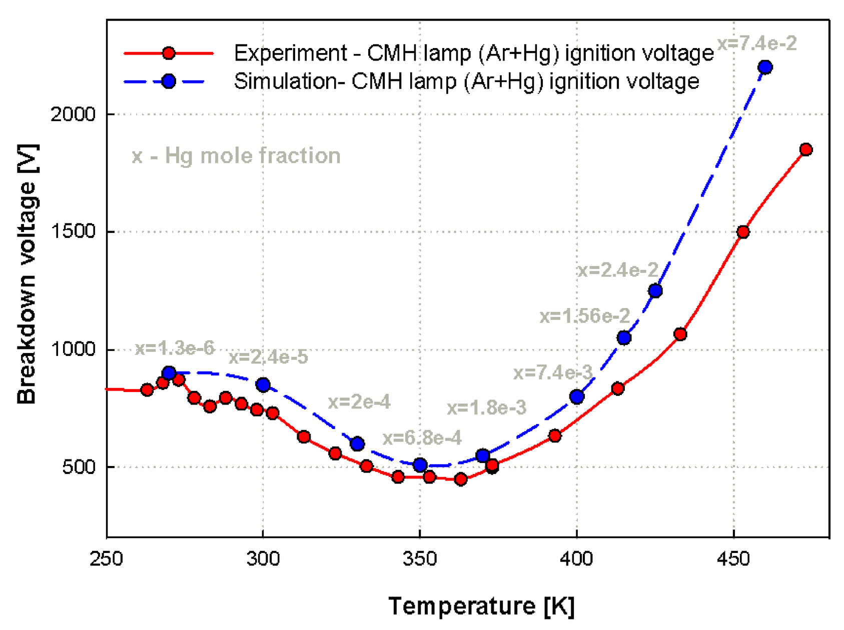
Electron collision cross sections

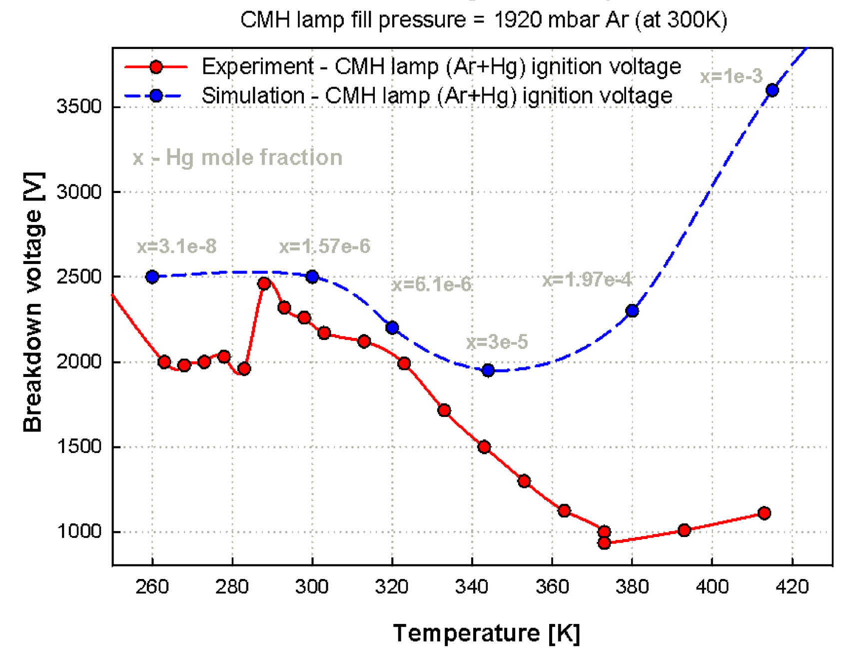
Results

BREAKDOWN VOLTAGE: SIMULATION VS. EXPERIMENT







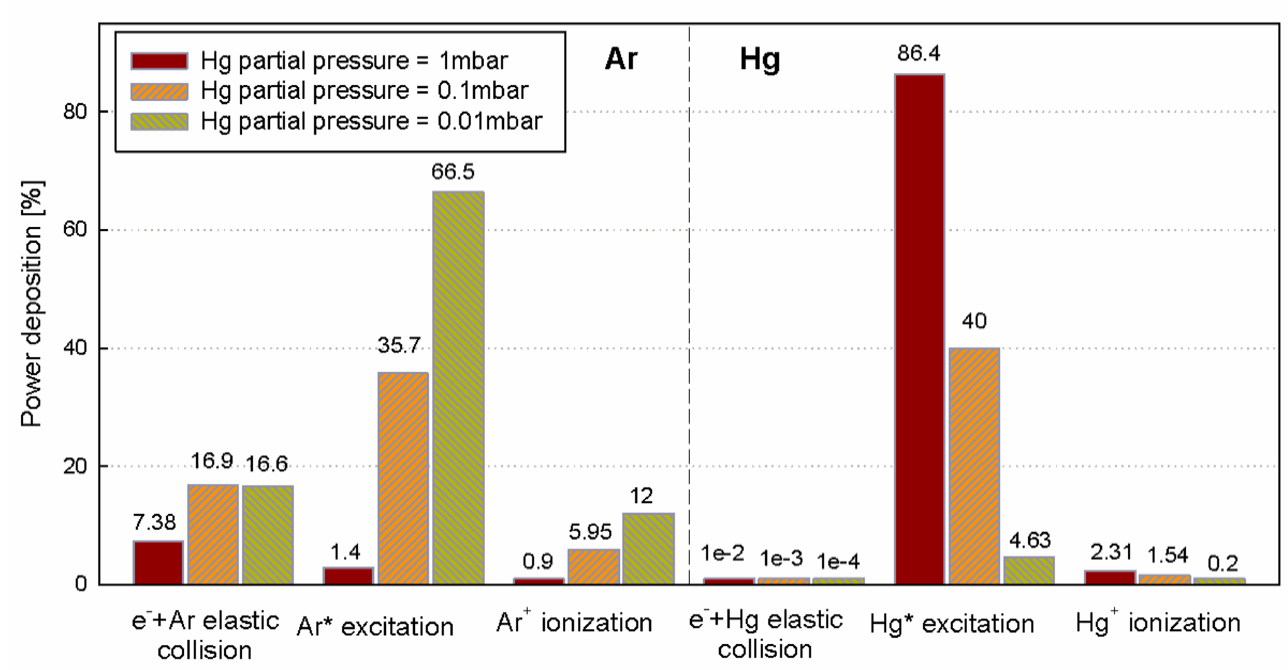


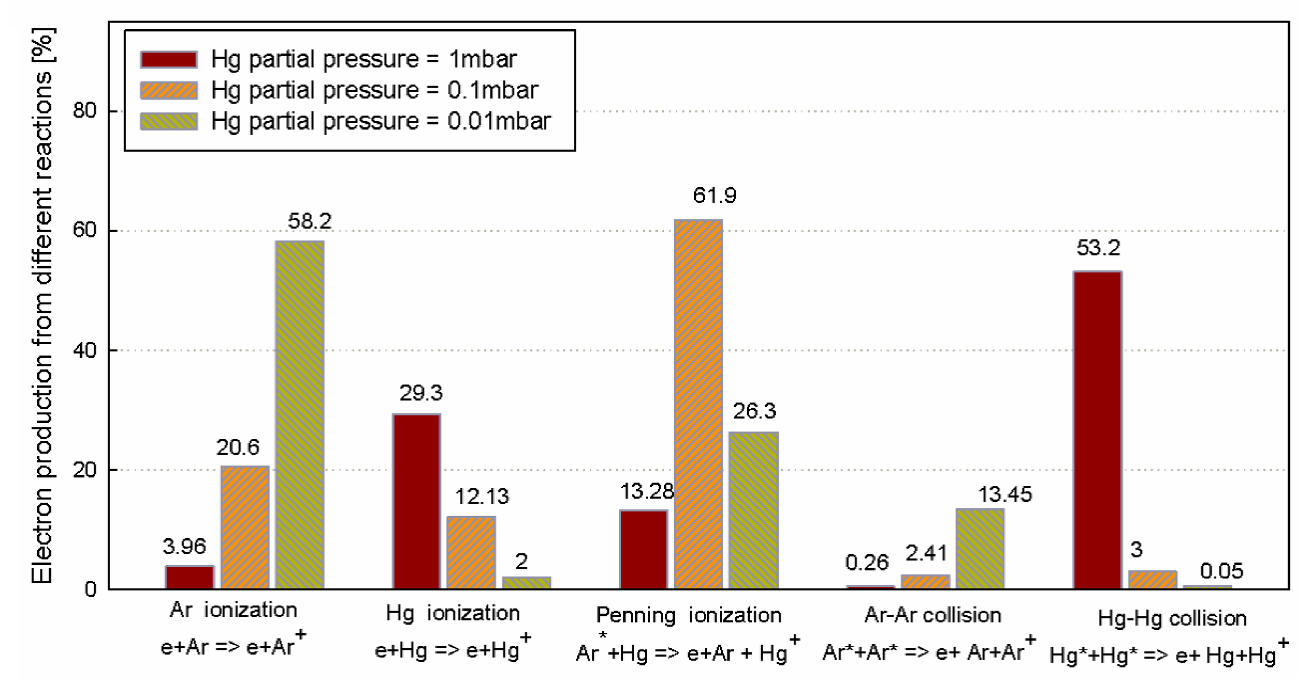
Experimental and simulation values of breakdown voltage at 192 mbar and 1920 bar Ar CMH lamps (at 300K). Hg vapor pressures are function of lamp pressures.

The Penning effect has a strong influence on the breakdown voltage, therefore this phenomenon is often used to lower the breakdown voltage in discharge lamps. Excited Ar atoms can ionize ground state Hg atoms, hereby producing significant number of free electrons.

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.

AR+HG MIXTURE OPTIMAL RATIO : MAXIMIZING PENNING EFFECT





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.

Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan