Influence of Thermal Conductivity and Plasma Pressure on Temperature Distribution and Acoustical Eigenfrequencies of High-Intensity Discharge Lamps

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Abstract

High-intensity discharge (HID) lamps are energy-efficient light sources with excellent color qualities. These HID lamps are operated on low frequency square wave drivers with a high-frequency ripple. A cost reduction and efficiency step can be made by operating these lamps on high-frequency electronic ballasts [1]. However, these tend to excite acoustic resonances inside the arc tube (Figure 1) that lead to arc flicker. More recently, the mechanism behind this phenomenon has been identified [2]: Alternating electric current represents a periodic heat source in the arc tube. The resulting temperature fluctuations imply pressure oscillations. Operating the ballast at an Eigenfrequency (EF) induces standing pressure waves, which affect the velocity field of the plasma constituents so that arc flicker occurs.

A three-dimensional model of a low-wattage lamp, which includes plasma, electrodes, and burner walls, was developed in COMSOL Multiphysics® [3]. Most parameters appearing in the coupled differential equations of the model, such as viscosity, thermal and electrical conductivity are temperature-dependent. In order to investigate the influence of material properties and the plasma pressure on the temperature distribution and the corresponding Eigenfrequencies, a sensitivity analysis was performed. The experimental validation was conducted by measuring the voltage drop between the electrodes at different driving-frequencies.

Based on the assumption of local thermal equilibrium (LTE) of the plasma constituents model functions of variable electrical conductivity have been derived [4]. Below a temperature threshold of about 3500 K the assumption of LTE is inappropriate [5]. Therefore, a temperature independent non-LTE conductivity was assumed beneath this threshold (Figure 2).

The spatial temperature distribution and the second acoustic Eigenfrequency depend on the choice of the threshold (Figure 3). For low values of the non-LTE threshold the temperature in the hot plasma column is rather uniformly distributed. Only the temperature of the electrode sheaths is higher. Increasing the non-LTE threshold leads to a lower plasma temperature and an increasing Eigenfrequency. Once the plasma column reaches a temperature below the non-LTE threshold, the plasma column is separated by an area of lower temperature and the Eigenfrequency decreases. The second Eigenfrequency could be confirmed experimentally because light flicker occurred at 42.1±0.5 kHz, which is close to the average of the simulation

results of 44.5 kHz.
In a second investigation the temperature distribution and the Eigenfrequencies at different plasma pressures were investigated. With exception of the cathode sheath, the temperature is independent of pressure (Figure 4). However, higher pressures cause larger buoyancy forces that implicate stronger arc bending. Due to the related change in the temperature distribution, the second Eigenfrequency slightly decreases with increasing pressure.
The sensitivity analysis shows that precise material data is crucial for the significance of simulation results. The plasma reacts more sensitive to changes of the electrical conductivity than to variations of the pressure. In particular, the temperature profile depends on the details of the material models. In a next step the arc shape will be detected by a photo detector to implement a second validation criterion.

Reference

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[5] Peter Flesch, Manfred Neiger, Understanding Anode and Cathode Behaviour in High-Pressure Discharge Lamps, J. Phys. D: Appl. Phys., 38, 3098-3111(2005).

Figures used in the abstract

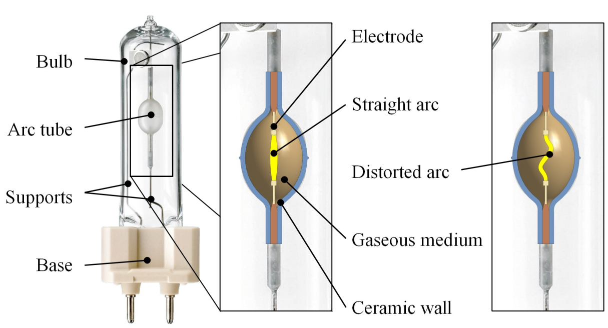

Figure 1: Arc perturbation by acoustic resonances inside the arc tube of HID lamp

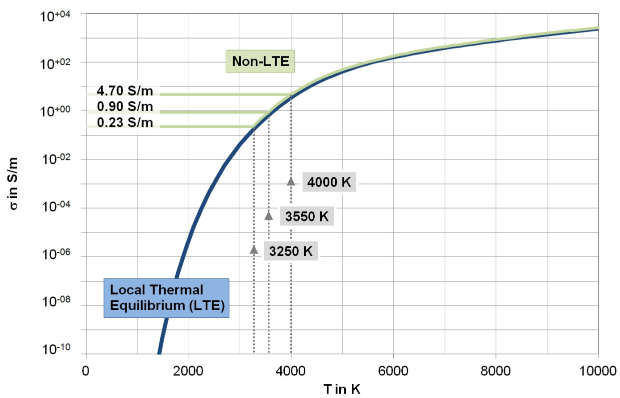

Figure 2: Temperature-dependent electrical conductivity of plasma

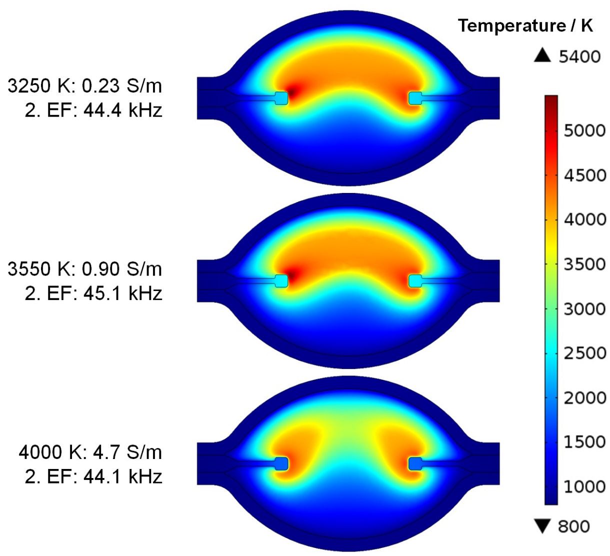

Figure 3: Temperature distributions at different electrical conductivities and their influence on the frequency of the second Eigenmode

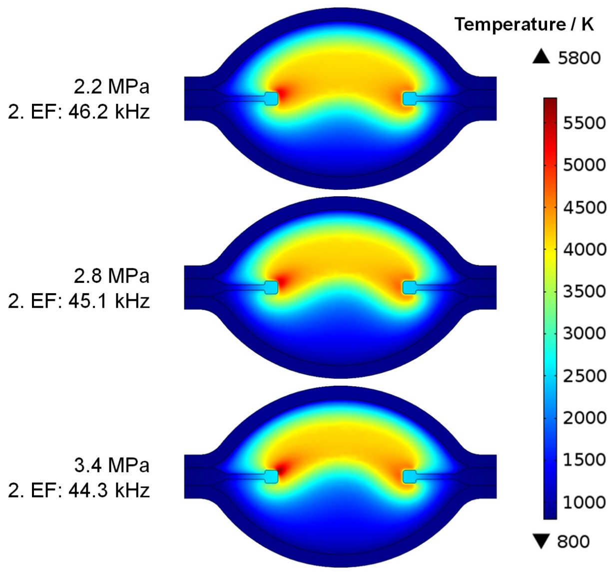

Figure 4: Temperature distribution at different plasma pressures and their influence on the frequency of the second Eigenmode