Summary

Transport phenomena in metal-halide lamps, a poly-diagnostic study

Worldwide about 20% of all electricity is used for lighting. It is therefore of great interest to develop a lamp that has high efficacy, good colour rendering and long lifetime. The metal-halide lamp is a gas discharge lamp that meets all these demands. Unfortunately there are still issues with this lamp that need to be dealt with in order to maximize its full potential.

One of these issues deals with the orientation dependence of the light-technical properties, such as colour reproduction and efficiency. Moreover, when the lamp is operated vertically, it can become unstable and is non-uniform in colour. The additive metals in the metal-halide lamp are not evenly distributed over the lamp, they are segregated. In this case, most of the metals can be found at the bottom of the lamp. This results in poor colour rendering and a decreased efficiency. It is therefore of interest to gain a better understanding of the complex transport phenomena so that the design of the metal halide lamp can be improved. A good numerical model can help achieve this goal.

The objective of this thesis was to accumulate a large amount of data under a variety of conditions so that the numerical model can be validated and insight into the complex transport phenomena can be improved. It is however currently beyond our capabilities to fully understand and model a commercial metal-halide lamp with a complex shape and chemistry. Therefore, the measurements have been performed on a reference lamp with a simple geometry and chemistry. The lamp that was mainly studied in this thesis contained only one salt, namely DyI_3. The last chapter of this thesis is devoted to the study of a commercial lamp.

A poly-diagnostic approach was used to investigate the plasma properties of the metal-halide lamp. Optical emission spectroscopy (OES) was used obtain information of the wavelength spectrum. Compact and robust setups were used under extreme gravity conditions. X-ray diagnostics that were applied were x-ray absorption spectroscopy (XRA) and x-ray induced fluorescence (XRF). X-ray absorption measures the Hg density at high spatial resolution allowing for an accurate measurement of the heavy-particle temperature.

The Advanced Photon Source at the Argonne National Laboratory was used to excite XRF in the metal-halide arc. XRF allows for direct measurement of the arc constituents, Dy, I and Hg. The spatial distribution of the additives and Hg were determined and from

these the concentration profiles of the additives. These showed significant radial and axial segregation for Dy and much less for I.

The OES measurements showed the distribution of the excited states of Dy and Hg. Absolute line intensity measurements were done using a 1-m Czerny Turner monochromator which was used to measure a large part of the visible spectrum. From the radially resolved spectral lines an Atomic State Distribution Function (ASDF) was constructed. From the ASDF several quantities were determined as a function of radial position, such as the (excitation) temperature, the ion ratio Hg^+/Dy^+, the electron density, the ground state and total density of Dy atoms and ions.

Both the lateral and radial profile of the individual lines show that there is a clear separation between the ionic and atomic regions of Dy. The Dy atoms have a hollow density profile whereas in the centre the atoms are ionised. In the outer parts of the lamp molecules dominate. Ionic Hg is found in the centre of the lamp, where the temperature is highest. The ion ratio Hg^+/Dy^+ showed that the Hg ion dominates in the centre of the lamp.

Prolonged micro-gravity conditions were obtained at the international space station (ISS). At 0-g there is no convection, only diffusion. The webcam images taken at the ISS showed, as expected, that there is no axial segregation, only radial. Because the micro-gravity environment eliminates convection, it is easier to model. The density distributions, concentration profiles and temperature profiles measured at micro-gravity were compared to the model. The model and experiment were in reasonable agreement with each other. The comparison has given us further insight in the various phenomena, the model has guided the interpretation of the experimental results with respect to the deviation of LTE whereas the experiment has indicated which set of elementary parameters is essential for the theoretical description of the lamp as a whole.

When the lamp was placed in a centrifuge and subjected to hyper-gravity up to 10 g, the species are mixed by the increased convection, causing the Dy to be better distributed over the lamp. Atomic lateral profiles of Dy at different axial positions in the lamp were used for the calculation of Fischer's axial segregation parameter. The theoretical model of the Fischer curve, which shows the axial segregation parameter as a function of convection, was verified along the full range by measuring lamps of different filling and geometry.

We used XRA of the Hg density in the lamp to determine the gas temperature, it was found that scattering of the x-rays on the lamp materials have a profound effect. The electron temperature measured by OES and gas temperature measured by XRA shows a central axis temperature of 6000 K. This would suggest that the LTE assumption in these lamps is justified. However, a more in depth study showed that in the outer regions of the discharge a deviation of LTE occurs. Nevertheless, it is expected that the LTE deviation will not have a major impact on the determination of the main plasma parameters.