9

Conclusions

9.1 Introduction

The aim of the research described in this thesis was to obtain a better understanding of the transport phenomena of the chemically complex plasma of the metal halide lamp. By comparing the model results to the experiments we can gain insight into the complex transport phenomena in the metal-halide lamp. The experiments verify the model results, whereas the model gives insight and aids the interpretation of the experimental results. The experiments at micro-gravity are part of a poly-diagnostic study [1–9] of the metal-halide lamp. The individual results of the experiments also validate each other and give insight into the plasma processes. This thesis has dealt with the experimental investigations. In this chapter we give an overview of the conclusions of the different chapters. This can be divided into three parts, the optical emission spectroscopy measurements (OES), the comparison to the model, and the x-ray spectroscopy experiments. The LTE (Local Thermal Equilibrium) assumption is investigated by comparing the results from the x-ray spectroscopy and the emission spectroscopy, and by combining the latter results at micro-gravity with the results from the numerical model. We conclude this chapter with a general outlook.

9.2 Overview of the thesis

9.2.1 Optical emission spectroscopy

The optical emission spectroscopy (OES) experiments can be divided into two types of diagnostics. The first type of measurement was done using a 1-m Czerny-Turner monochromator under normal gravity conditions. The monochromator was used to measure the transitions of Hg and a large number of transitions for Dy for a majority of the visible range (between 400 and 700 nm). The second type of measurement was done using an Echelle spectrometer at gravity conditions ranging from micro-gravity up to hyper-gravity. The Echelle spectrometer was chosen because it is small, compact and does not contain moving parts. Several interference filters were used for wavelength selection, in this way a few transitions of atomic and ionic Dy, and atomic Hg have been measured. In both cases the lines were measured along the line of sight, yielding a profile of the line intensity as a function of lateral position for each line. This profile was then Abel inverted so that the radial intensity profile was obtained.

The OES measurements showed the distribution of atomic and ionic states of Dy and atomic Hg. 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. The Dy ions also show a dip in the centre, there Hg ions are found to dominate. In the outer parts of the lamp molecules dominate.

Absolute line intensity measurements at normal gravity

As reported in chapter 2, a myriad of Dy lines were measured with the 1-m Czerny-Turner monochromator, a total of 39 of these lines were chosen. From these atomic and ionic Dy lines, the radial intensity profiles were determined. With the help of these atomic and ionic Dy intensity profiles we constructed the radially resolved Atomic State Distribution Function (ASDF). From these ASDFs several quantities were determined as 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. The density of the Dy atoms is found to be 10^{20} m^{-3} for a lamp burning at 100W. The ion ratio Hg^+/Dy^+ showed that in the centre Hg ions dominate. The axis temperature measured with atomic Dy, ionic Dy and Hg showed an axis temperature of 6000 K within the 10 % error margin. The ASDF of Dy^+ also showed that LTE is no longer valid in the outer regions of the discharge.

MH lamps at gravity conditions ranging from 0-g to 10-g

The investigated lamp was designed such that axial segregation is at its maximum value under normal gravity conditions. In order to study the roles of the competing processes of convection and diffusion separately, the lamp was subjected to extreme gravity conditions. Two extreme conditions were created during the parabolic flight experiment, i.e. no convection (micro-gravity) and enhanced convection (2-g). At micro-gravity there is no convection, so that the segregation is only present in radial direction. At hyper-gravity, convection dominates and axial segregation can be varied depending on different gravity conditions. Because the gravity conditions could not be maintained long enough during the parabolic flights for the discharge to stabilise, and because it is of interest to increase the dynamic range of the hyper-gravity experiments, the lamp was placed in the international space station (ISS) and the centrifuge. The results from the extended micro-gravity conditions are reported in chapter 3. The centrifuge can increase acceleration up to $10g$, the results of the experiments done under these conditions are reported in chapter 4.

Microgravity

An Echelle spectrometer was used for the optical emission spectroscopy (OES) measurements at prolonged micro-gravity conditions 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.

The atomic Hg line was calibrated and in combination with the vapour pressure used to calculate the radial temperature profile. By combining the radial temperature profile with the calibrated radial intensity profile of the additive, the absolute radial density profile of the total atomic and ionic density of Dy was obtained. Lamps containing Dy showed contraction of the arc, which increased for higher powers. Comparison between 0-g and 1-g showed that there is more radial segregation at 0-g. This is because of the absence of convection at 0-g, which promotes mixing of the species. The temperature profile of a lamp containing both Hg and Dy showed an axis temperature of 6100K at 1-g, which is comparable to the axis temperature at 0-g within the error margin. The difference between 1-g and 0-g of the radial temperature, intensity and density profiles, decreased for high powers. Atomic density for a lamp operating at 110 W at 1-g is found to be about 10^{20} m^{-3} at the centre of the lamp, which is comparable to what is found by the absolute line intensity measurements done in chapter 2.

Hypergravity

The setup, comparable to the one used at the ISS, was placed on a centrifuge. This centrifuge accelerated the OES setup and lamp between 1 and 10-g, thereby enhancing the role of convection.

Several transitions of atomic and ionic Dy, and atomic Hg have been measured at different lateral positions from which we obtained atomic and ionic Dy and atomic Hg intensity profiles. These profiles were determined at different axial positions in the lamp. Both ionic and atomic Dy profiles showed, for burners with low aspect ratio that at higher g, the amount of Dy decreases near the bottom and increases near the top.

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. Moreover, the radial temperature profile of the arc for the different gravitational accelerations was determined. The temperature profile near the lower electrode, showed contraction at high g. This is causes by the increase of convection.

9.2.2 Comparison with the numerical model

The numerical simulations done by M.L Beks with Plasimo were compared to the experimental results in order to verify the results of the model and to gain a better understanding of the transport processes, which is the final goal of the overall project. A start with the validation was made in chapter 5 where the results of the model were compared to the micro-gravity experiments. As there is no convection this allows for easier modelling.

The model and experiment are in reasonable agreement with each other. The cross-section for the elastic collision between the Dy ion and Hg atom was approximated by the Langevin cross-section. The sensitivity of the plasma properties for this cross-section was investigated. The temperature profile is in agreement and not too sensitive for the choice of cross-section. Dy atom profiles showed an abrupt transition between atom and molecule for both model and experiment. The comparison between the experiment and model results for the Dy atom concentration showed that the model predicts too much radial segregation. Both the atom and ion distribution is very sensitive to the choice of cross-section for the collision between the Dy ion and Hg atom. The ratio Hg^+/Dy^+ was found to be extremely sensitive for the cross-section of the elastic interaction $\sigma(Hg, Dy^+)$ between Dy^+ and Hg atom. The sensitivity analysis reveals that equating $\sigma(Hg, Dy^+)$ to a value that is 10% higher than the Langevin cross-section is the best choice.

There is a clear discrepancy between experiment and the LTE-based model for the Dy ion density profiles. The experiment shows that the Dy ion density decreases much more rapidly. Further analysis into the Boltzmann-Saha balance suggested that after $r/R >$ 50% LTE is no longer valid.

9.2.3 X-ray diagnostics for MH lamps

It is desirable to use a technique that can penetrate all regions of the lamp and can directly measure the absolute density of the detected element. It is because of these advantages that two different x-ray diagnostic techniques were used. X-ray induced fluorescence (XRF) is capable of directly measuring all elemental densities of the arc constituents so no Abel inversion is needed. The data-analysis is therefore much less complicated. Unfortunately the spatial resolution of XRF is not very high. The experiment and results are discussed in chapter 6. X-ray absorption measures the Hg density, combined with the wall temperature and the ideal gas law $p = nkT$, the temperature profile was obtained. XRA has much higher spatial resolution compared to XRF. A high spatial resolution is needed near the wall because of the steep temperature gradients. However, in contrast to XRF, the data-analysis XRA is much more complex. The x-ray absorption of Hg are described in chapter 7 and 8. The latter deals with the measurement of a commercial lamp.

X-ray induced fluorescence

Synchrotron radiation from the Advanced Photon Source at the Argonne National Laboratory was used to excite fluorescence in the arc constituents. Elemental densities of Hg, Dy and I were measured. In order to study the segregation effect the elemental concentration of I and Dy were determined.

Significant radial and axial segregation of Dy were observed. Elemental I is seen to exhibit considerably less axial and radial segregation. Some aspects of the observed radial segregation are compatible with a simplified analytical fluid model describing two main transition regions in the radial coordinate. The first transition occurs in the region where DyI_3 molecules are in equilibrium with neutral Dy atoms. The second transition occurs where neutral Dy atoms are in equilibrium with ionized Dy. The segregation parameter of Fischer for Dy and the Dy elemental density is in agreement with Laser Absorption Spectroscopy (LAS) measurements done by Flikweert. The LAS measurements also reported 10^{21} m^{-3} at the centre for a lamp burning at 151 W, which is comparable to the 10^{21} m^{-3} measured with XRF at the centre for a lamp operating at 145 W; both were measured at the midplane.

X-ray absorption

The experiment and data-analysis devised by X. Zhu was improved. Three phenomena were investigated that have an effect on the final outcome of the experiment. The ideal Tikhonov parameter was found and the Abel inversion was improved by increasing the number of polynomial terms.

Beam-hardening, which occurs when the source is not monochromatic, was studied and found to be negligible within our error margin. The scatter of the x-rays on quartz was studied experimentally and was found to be significant. By incorporating the scatter-correction, and optimising the regularised Abel inversion, we found that the axis temperature is 6000 K for the lamp containing DyI_3. This is in agreement with the optical emission spectroscopy studies mentioned above and in chapters 2,3 and 4.

Two sets of measurements were done. The first set included two lamps both containing quartz burners, with and without salt (DyI_3). This and the investigations described above were presented in chapter 7.

Chapter 8 deals with x-ray absorption measurements of 4 ceramic lamps with different fillings, namely, DyI3, TlI, NaI and a commercial lamp containing a mixture of these three. The commercial metal-halide lamp temperature profile combines the effects of its various salt constituents. These are mainly Dy, Na and Tl. Dy causes the profile to contract, whereas Na tends to broaden the profile, cancelling the contraction caused by the Dy. Tl has a pronounced effect on the shape of the temperature profile of a pure Tl lamp. The temperature profiles clearly show a region where the atoms associate into molecules, and vice versa, which results in the presence of 'shoulders' in the temperature profile. A reproducibility study pointed out that the error in axis temperature is about 8 %, while for the profile shape an error around 1.6% was found.

9.2.4 LTE validation

A system is said to be in Local Thermal Equilibrium (LTE) when two conditions are fulfilled, 1) all material particles (species) have the same temperature, 2) The distribution of atoms, ions and molecules over internal states obey the laws of equilibrium statistical mechanics. This is of particular importance for the numerical model. If the LTE assumption is justified this can substantially simplify the numerical model. It is therefore of interest to verify the validity of the LTE assumption. Optical emission spectroscopy measured the excitation temperature. Assuming most of the excitation occurs by electron collision and that transport phenomena are negligible, we can presume that the excitation temperature equals the electron temperature.

We used x-ray absorption of the Hg density in the lamp to determine the gas temperature. Both the electron (excitation) and gas temperature is found to be around 6000 K. This would suggest that the LTE assumption in these lamps is valid within the experimental error of the methods. However, both the ASDF of the Dy ion and the comparison between numerical model and experiment revealed that in the outer regions the LTE assumption is no longer justified. However, this departure of LTE only has a limited effect on the main plasma parameters such as the temperature and the electron density. It will also not substantially change the spectrum emitted by the plasma. This means that using an LTE model is justified to describe the phenomena in this type of lamp.

9.3 General outlook

A large amount of data has been collected using both optical and x-ray diagnostic techniques. The plasma parameters, namely density and temperature, were investigated under different gravity conditions and with two types of x-ray diagnostics. The information gathered can be seen as a basic data set for the validation of numerical models. Also, the data was used to cross-compare the results of the various experiments. Insight into the effect of the metal iodides on the arc, and the diffusion and convection processes was gained.

There are other experimental studies of the metal-halide lamp that are either ongoing or of interest to pursue in the future. Laser Absorption Spectroscopy (ILAS) measurements at gravity conditions of varying degree is currently performed by Flikweert [14]. ILAS measures the ground state density of the Dy atom. Thomson scattering [10, 11], which allows for direct measurement of the electron temperature and density can help shed light on the validity of the LTE assumption, which is of vital importance for the model. It would be interesting to investigate the role of the molecules with emission spectroscopy or Laser Induced Fluorescence (LIF) [12, 13]. Finally, time-resolved measurements have shown interesting effects such as cataphoresis, which require further study.

The final goal would be to obtain a numerical model, so that the metal-halide lamp can be designed to function most efficiently, with more stability, longer lifetime and better colour rendering. The results presented in this thesis here are indispensable for the development and testing of such a model.

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