Cathode and anode research

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Abstract: *Considerable advances in theoretical and experimental investigation of electrode phenomena in high-intensity discharge (HID) lamps have been attained during the last decade. The aim of this talk is to deliver a concise review of the understanding achieved.*

INTRODUCTION

A necessary condition to achievement of high performance of HID lamps is a long enough life of electrodes, typically of order of tens thousand hours. An inadequate arrangement of current transfer to electrodes can cause strong erosion of electrodes and deposition of the electrode material on the walls of the lamp (blackening), with catastrophic consequences for the lamp efficacy. Therefore, a proper design of the electrodes is of crucial importance. This applies primarily to cathodes, since anode effects are believed by many authors to be less critical to performance (e.g., [1]). In spite of many decades of intensive experimental and theoretical research, understanding of the whole physical picture, reliable experimental data, self-consistent theoretical models, and methods of simulation of plasma-electrode interaction in HID lamps started to emerge only in the late 1990s. The aim of this talk is to deliver a concise review of present understanding of electrode phenomena in HID lamps.

The topics covered in the talk are as follows: simple estimates for conditions typical for HID lamps are given with the aim to explain, starting from the first physical principles, why the physics behind the near-cathode and near-anode phenomena is essentially different; present understanding of near-cathode phenomena in HID lamps is given; results on near-anode phenomena are discussed, including both results obtained directly for conditions of HID lamps and results that can be rescaled to these conditions.

UNDERSTANDING DIFFERENCES BETWEEN THE CATHODE AND THE ANODE PHYSICS

The increase of the electron temperature in front of the electrode caused by current constriction in the quasi-neutral plasma is estimated. Densities of the ion and electron diffusion currents from the quasi-neutral plasma to the edge of the near-electrode space-charge sheath are evaluated, as well as densities of the ion and electron saturation currents from the quasi-neutral plasma to the edge of the near-electrode space-charge sheath. It is found that the density of electron diffusion current is by one or more orders of magnitude higher than a characteristic density of the net electric current on the electrode surface. On the other hand, the density of the ion saturation current is by one or more orders of magnitude lower than a characteristic density of the net electric current on the electrode surface. This is the root cause of the difference between operation of the anode and the cathode. On the anode, the role of the space-charge sheath consists in repelling 90% or more of electrons coming to the sheath edge from the quasi-neutral plasma. In other words, the anode is under a negative potential with respect to the sheath edge (i.e., with respect to the quasi-neutral plasma), i.e., the anode sheath voltage is negative.

In the case of the cathode, the rise of the electron temperature caused by current constriction in the quasi-neutral plasma is insufficient to provide the charged particle density needed to sustain current. Hence, an additional heating of the electrons in front of the cathode is needed, and this heating may come only from acceleration in the sheath of the electrons emitted by the cathode surface. In other words, while the sheath on the anode plays a passive role, the sheath on the cathode is active.

UNDERSTANDING OF NEAR-CATHODE PHENOMENA IN HID LAMPS

The next topic to be addressed in the talk is the present understanding of near-cathode phenomena. Power balance of the near-cathode plasma layer is discussed. The densities of thermal fluxes from the plasma to the near-cathode layer transported by the electrons and by the heavy particles have opposite directions and virtually cancel. Therefore, near-cathode layer is independent of the bulk plasma. As a consequence, the plasma-cathode interaction in HID lamps is independent of the bulk plasma and may be modeled independently; the so-called model of nonlinear surface heating. By now, this model has been validated by detailed electrical and thermal measurements and has become more or less universally accepted. It should be stressed that this model allows one to self-consistently model diffuse and spot modes of current transfer to HID cathodes, without the necessity to artificially "switch" between different modes [2].

Basic ideas of the model of nonlinear surface heating are discussed. The most important results obtained in the framework of this model are considered. Experimental results are discussed and compared with theoretical data. Stability of different modes of current transfer is discussed. A free online tool for simulation of axially symmetric modes of current transfer is demonstrated. Other topics to be dealt with include modeling and experimental investigation of transient effects; modeling of cathodes of a complex shape made of different materials; modeling of multispecies plasmas with complex chemical kinetics (plasmas of metal halides), also with account of variation of the work function due to deposition of a monoatomic layer of an alkali metal.

REASULTS ON NEAR-ANODE PHENOMENA

Another topic to be addressed in the talk is concerned with near-anode phenomena. Unfortunately, reliable results obtained for conditions of HID lamps have started to appear very recently (e.g., [3]) and are yet scarce. This is likely to be a consequence of two factors: first, the above-mentioned traditional belief that anode effects are less critical to performance of a lamp than cathode effects; second, mathematical problems describing the plasma-anode interaction are not that clear-cut as the model of nonlinear surface heating, since a theoretical description of plasma-anode interaction cannot be decoupled from a modeling of the arc column and of the constriction zone. On the other hand, very interesting works have been published recently on near-anode phenomena in high-current arc discharges.

In this talk, experimental results obtained recently for conditions of HID lamps are discussed, as well as experimental and modeling results on high-current arc discharges that may be re-scaled to conditions of HID lamps.

CONCLUSIONS

Decisive advances in theoretical and experimental investigation of plasma-cathode interaction in high-intensity discharge lamps have been attained during the last decade; in some aspects, the understanding is virtually complete. Understanding of the anode phenomena is much less complete; however, one can hope that rapid progress will follow.

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