

Gravity's pull on arc lamp efficiency

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Whenever humans are present artificial light is used. It allows us to live and work indoors and outdoors at any time of the day. In densely populated areas, this literally lights up our planet as is clearly seen from outer space in figure 1. The 30 billion lamps operating worldwide are certainly a great commodity, but they come at a price. Not only do they cause serious light pollution, disturbing animal and plant life, they also have a huge energy need. Of the annual world electricity production, which is more than 10^{13} kWh, about 15-20 % is used for lighting applications [1]. A medium- to large-sized electricity plant has a production capacity of about one GW. An easy calculation shows that a few hundred electricity plants are operating continuously solely to supply the power for our lamps. Apart from depleting fuel reserves, this also results in an annual CO_2 emission of about a billion ton and the attendant effects on ecology and climate. Obviously, lighting has a large social, economical as well as ecological impact.

The best known lamp type is the incandescent lamp, where an electrical current heats a wire until it lights up. More than 100 years after Edison's invention, modern incandescent lamps are still not very efficient. Incandescent lamps produce only about 3% of all light whereas they consume 20% of the power needed for lighting. Discharge lamps are about 5 to 10 times more efficient. They can be grouped into two large families based on operating pressure. Tubular fluorescent lamps, commonly used in offices, are the best-known example of low pressure lamps. High pressure lamps are commonly used if much light is needed, such as outdoor lighting. About 97% of all artificial light on Earth is produced using plasma technology [1, 2]. Evidently, plasma lamps are essential in lighting, and any increase in their efficiency, even by as little as 1%, has a large impact on preserving our natural resources and environment.

The metal halide lamp is a high-pressure gas discharge lamp with a very high efficiency. Despite the fact that the lamp is widely used in outdoor lighting there are still several technological and scientific problems limiting its applicability. Some of the problems are related to a poor understanding of the physics of the gas discharge. Color separation, discussed here is one of them. But before describing the problem and discussing some experiments one should first review the basics of a metal halide lamp.

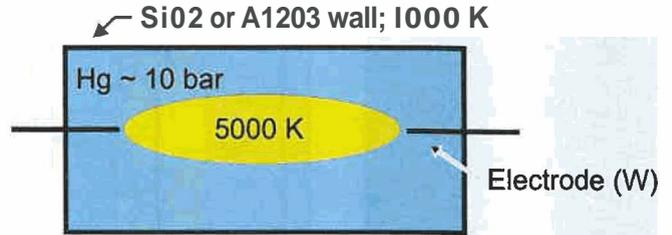


Fig. 2: A schematic view of a metal halide lamp. The arc is produced between two tungsten electrodes in a mercury buffer gas of about 10 bar. The arc is confined inside an SiO_2 or Al_2O_3 burner. Furthermore, a metal halide salt like NaI , DyI_3 , ScI_3 , or TlI is added. After evaporation and dissociation, the excited metal atom is the main radiation source.

Metal Halide Lamps

A metal halide lamp is derived from the better known mercury high-pressure arc discharge [2]. A schematic picture is shown in Fig. 2. An electric arc is maintained between two electrodes, which are sealed into the confining space of the lamp burner. In normal operation, the main gas in the lamp is mercury. Depending on lamp type, size, and application; the pressure varies from a few to several hundred bars. The former are large lamps used as street or stadium lights, the latter are tiny lamps used in video and beamer projection systems. The centre of the arc is at a temperature of about 5000 K, while the wall is maintained around 1200 K. As the lamps are in the millimeter to centimeter size range, this implies that there are strong temperature gradients. A high voltage peak starts the lamp in a noble gas, but after a few seconds the mercury begins to evaporate. Due to its lower ionization energy, the arc soon becomes a mercury discharge. Mercury discharges are very efficient, and commonly used as lamps. The main mercury emission lines, however, are in the W region. To obtain visible light a fluorescent coating on the lamp is needed, which transforms one UV photon into one visible photon. It is the white coating on the tubular fluorescent lamps that we "see" not the W-light generated inside the discharge. The lamp color is optimized by mixing different coatings and not by changing the discharge. Unfortunately, the energy of a visible photon is about half that of the W photons, so the energy of mercury emission is only partly utilized. Metal halide lamps use the efficiency of a mercury discharge, while directly emitting visible photons. Thus there are no fluorescent coatings. This is achieved by adding a mixture of metal halide salts (such as DyI_3 , ScI_3 , CsI_2 , or NaI) to a mercury arc discharge. Obviously, in the hot central arc region, the salt will dissociate and the metals will be excited and ionized. These metals are extremely efficient radiators. Even though the metal density is much less than the mercury density, most light is emitted by the metals in the visible region. As a result, metal halide lamps can be made, with power efficiencies up to 40%, significantly better than most other lamp types. A good color rendering is achieved by mixing various salts. Currently, these lamps are used for industrial lighting, street



Fig. 1: Artificially lit satellite view of discharge lamps. (© Photo: The ASA file)

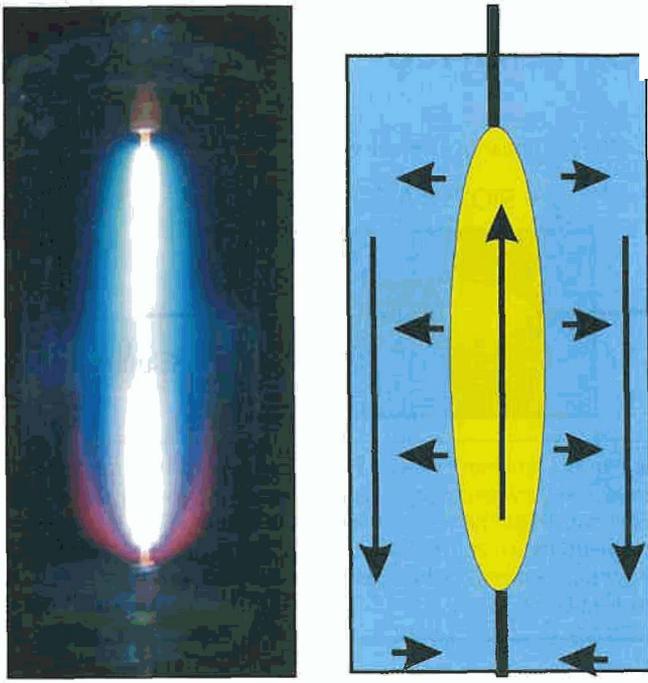


Fig. 3 Axial segregation and color separation in a vertically operating metal halide lamp due to the combined effects of diffusion and convection. a) A picture of the arc discharge with color separation. b) An artist impression of the diffusion and convection flows.

... lighting, and city beautification. Unfortunately, the lamp also suffers from several problems, which limit its use for other applications, such as shop and home lighting. These problems include electronic control of the lamp, burning orientation, (re-)ignition problems [2] and instabilities [3]. Another problem is color separation in metal halide lamps. This means that different parts of the lamps emit different colors [4, 5].

Before going into a detailed explanation of the effect and showing the experiments, this general description of a metal halide lamp should be concluded with a remark on mercury. As is commonly known, mercury is unhealthy and thus mercury-free lamps are desirable. However, mercury lamps in general and metal halide lamps in particular are highly efficient. In assessing the ecological impact it should be noted that there are small amounts of mercury in the average fuel mix of electricity plants. During the long lifetime of these discharge lamps, generally about five to ten times more mercury is released into the atmosphere by electricity plants supplying the lamp power, than is present in the lamp. Moreover, the mercury in these lamps is easily recyclable. Since current mercury-free lamps are less efficient, there is no good alternative to the mercury-containing lamps for general lighting applications. Therefore it is important to understand how they work in order further to improve their performance.

Color Separation

A metal halide lamp with color separation has different colors along its axis. As a result an object will appear differently depending on its illumination. For some applications this may not be a serious problem, but imagine if the fancy patterned shirt that you see in the mall appears to be plain white in the sunlight. Figure 3a shows an example of color separation in a lamp containing DyI_3 . Whereas the bottom of the lamp is white with a reddish glow around it, the top is green.

The emission in the lamp results from excited species of the metal salt. Even though the partial pressure of the mercury buffer gas is constant over the discharge, a complex interplay of diffusion and convection results in a non-homogeneous distribution of the radiating metals. Let us concentrate first on the radial direction. Going from the wall at about 1200 K to the arc core at 5000 K metal halide molecules will first dissociate and then ionize. The resultant density gradients cause strong diffusion fluxes, which are counteracted by the back-diffusion of other species: near the wall molecules diffuse inwards and atoms outwards, while near the centre atoms move inwards and the ions diffuse out. Unfortunately, the diffusion speed of the molecules is significantly smaller than that of the atoms due to their size and mass difference. Ions and atoms have similar masses, but ions diffuse faster due to ambipolar diffusion. This is a typical plasma effect: the lighter and more mobile electrons in the plasma are coupled to the charged ions by Coulomb interactions. This results in an enhanced ion transport, away from the hot plasma regions. In a stationary state with equal inward and outward fluxes, a lower speed is balanced by a higher partial pressure. The total effect is called radial segregation and results in a reduction of the partial metal pressure (in any chemical form) near the lamp center.

In addition to diffusion, there is also convection in the lamp. In a horizontally operating lamp, convection will counteract the diffusion as it effectively "mixes" the various lamp species. Unfortunately, in horizontally operating lamps, convection will also lift the hot arc into the curved shape: exactly the process from which an arc discharge derives its name. Thus upward convection brings the hot plasma region close to the cold wall, which at best lowers the lamp efficiency and in worse cases causes lamp failure. To prevent this, most high-pressure lamps are operated in a vertical orientation. In vertically operating lamps, convection causes an upward flow in the hot central arc region, which returns downwards along the cooler walls [4, 5]. The minority metal salt species follow the dominant mercury convection flow. However, due to radial segregation the metal that rises in the centre diffuses outwards to the wall and is transported down. The combined effect of convection and radial segregation is a decreased metal density in the upper part of the lamp (fig. 3b). Such axial segregation results in a non-homogeneous emission, called color separation, shown in figure 3a. The effect has a maximum if convective and diffusive flows are of equal magnitude. High convective velocities result in a good mixing of species thereby eliminating radial segregation. In the absence of convection, the lamp emission will be axially uniform but radial segregation is maximal.

This explanation, first described by Fisher [6], yields a reasonable qualitative description of the effect. However, quantitative models, needed to increase lamp efficiency, are not available. Discharge calculations of diffusion and convection in complex reactive mixtures with high temperature gradients are difficult and many thermodynamic data are not known. In addition the electrodes, the lamp geometry and wall material also affect the lamp behaviour. Experiments are necessary to provide input data and verify any model results.

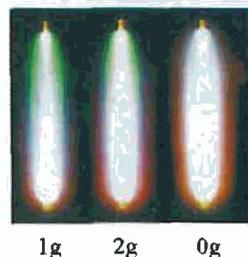


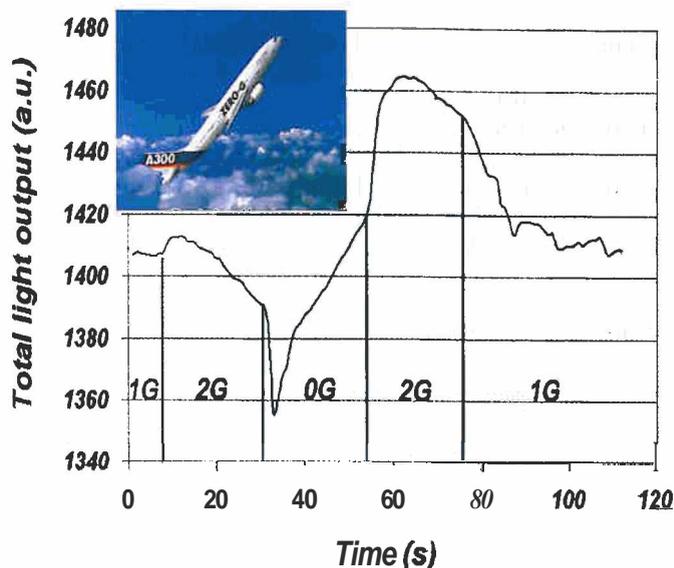
Fig. 4: Pictures of a metal halide lamp during normal gravity, hyper-gravity and microgravity. The differences in the emission profiles are "caused by a changing in the Dy distribution inside the lamp due to varying convection and diffusion flows."

Microgravity Experiments

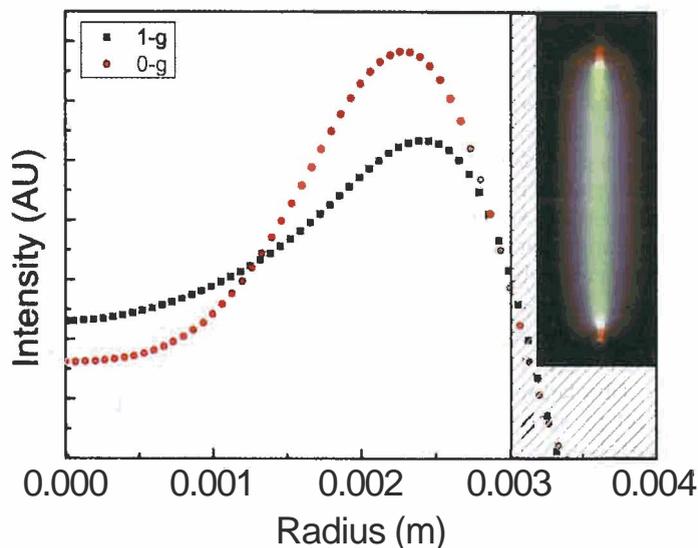
The previous discussion shows that diffusion and convection play a key role in understanding the lamp behaviour. To be able to unravel the complex interaction between convection and diffusion, extended experiments under zero gravity have been performed. In the absence of gravity, convection is eliminated, so the effect of diffusion can be studied undisturbed and compared with the model results. Parabolic free falls in an airplane have been performed in an airbus of the European Space Agency (ESA) and extended microgravity experiments were done in the International Space Station (ISS). During a parabolic flight, a level-flying airplane pulls up strongly before closing the engines and going into a parabolic free fall for about 20 s. At the end of the parabola, a second strong acceleration is used to prevent the plane from crashing. The result is that the plane is subjected to a series of 1.0–1.8–0–1.8–1.0 g gravity conditions. During the hyper-gravity (1.8 g) phases, there is an increased convection, whereas there is no convection during the microgravity phase.

Figure 4 shows pictures of a test lamp during various phases of the parabolic flight. At normal gravity conditions the color segregation is clearly visible, as the lower part of the lamp emits bright white light, whereas in the top part only weak mercury emission is seen. The lamp efficiency is measured by placing the lamp in an integrating sphere [7]. Such a sphere collects all lamp emission and determines the lamp efficiency by using an optical filter that imitates the human eye. The photographs in figure 4 show that segregation in the hyper-gravity phase is significantly less than under normal gravity conditions. This indicates that for this particular lamp increased convection results in a better mixing of the radiating metal species. The integrated sphere measurements (fig 5) confirm this as the total lamp emission increases during this phase. In the microgravity phase light emission is homogeneous in the axial direction. In this phase convection is absent so there is no axial segregation. Radial segregation dominates and depletes the central region of light emitting metal. This is visible in figure 5 as a decrease in the emission at the start of the microgravity phase. The subsequent increase is caused by an increase of the lamp temperature in the absence of convective cooling. A temperature increase results in a higher metal vapor pressure inside the lamp and thus a higher emission. It also shows that the 20 s of microgravity, available in an airplane, are insufficient to obtain a stable lamp. In order to study a fully stabilized lamp under microgravity conditions, measurements in the ISS are the only option. Under these conditions, there is no axial segregation and the lamp is completely homogeneous. Comparing spatially resolved spectral measurements from the ISS with those at normal gravity show a significant increase of radial segregation under microgravity conditions (fig 6). There is less metal in the center of the lamp as it diffuses outwards, resulting in a strong gradient of the partial pressure of the light emitting species. Obviously, these variations have a strong impact on the lamp emission and its efficiency. More details on the various measurements both under normal and microgravity conditions can be found in the references [8, 9].

It is 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 absence of convection under microgravity conditions greatly simplifies the problem. The measurements reveal a great deal about lamp behaviour, which needs to be reproduced by any valid lamp model. Qualitatively the lamp behaviour is well understood and the measurements supply ample data for the quantitative validation of a model. In addition, the measurements clearly show that there is still room ...



A Fig. 5: Light output of a 10 mg mercury lamp with Dyl_3 during a single parabola of an airplane. The light emission, measured using an integrating sphere, increases in the hyper-gravity phase. In the microgravity phase the emission decreases initially due to radial segregation but then starts to increase as more metal enters the lamp [7]. The inset shows the ESA plane during a parabolic flight (photo: ESA)



A Fig. 6: Light emission from excited atoms as a function of radial position in the lamp at normal (black squares) and micro-gravity (red dots) conditions. Due to dominant radial segregation there is less emission from the central lamp region under micro-gravity conditions. The microgravity measurements are performed in the international space station where the lamp shows no axial segregation as seen in the picture. The normal gravity data are taken with the same lamp just before launching. The data are reconstructed from spectrally resolved side-on measurements, which is reliable until the shaded area. [8]

... for efficiency gain. Obviously, changing gravity is not a practical solution, but it may help to identify how to optimize discharge parameters, so that we can light our world using less energy. %

About the author

Winfred Stoffels did his PhD on experimental plasma physics at the Eindhoven University in The Netherlands. After a two year period at the University of Kyoto, Japan, he returned to Eindhoven studying dusty, electronegative and molecular plasmas. Currently his focus is on the physics of gas discharge lamps in order to obtain more efficient light sources.

Acknowledgments

This work is a joint effort by the many people in the ARGES team (www.arges.tue.nl). It is sponsored by the Space Research Organization Netherlands, the Eindhoven University of Technology, Philips Lighting, the Netherlands Ministries of Education and Research and of Economic Affairs, Senter-Novem, COST, and STW. The support of ESA is acknowledged for the participation in the ESA parabolic Flight Campaigns and the Delta Soyuz mission. Particular thanks are due to astronaut André Kuipers, who performed the ISS measurements.

References

- [1] The International Energy Association (www.iea.org) and the International Association for Energy Efficient Lighting (www.iaeel.org).
- [2] G.G. Lister, J.E. Lawler, W.P. Lapatovich, V.A. Godyak, *Rev. Mod. Phys.* 76,541 (2004).
- [3] W.W. Stoffels, F.J. van den Hout, G.M.W. Kroesen, M. Haverlag, R. Keyser, *Appl. Phys. Lett.* 88,91502 (2006).
- [4] T. Nimalasuriya, A.J. Flikweert, W.W. Stoffels, M. Haverlag, J.J.A.M. van der Mullen, N.B.M. Papat, *J. Appl. Phys.* 99,53301 (2006).
- [5] A.J. Flikweert, T. Nimalasuriya, C.H.J.M. Groothuis, G.M.W. Kroesen, W.W. Stoffels. I. *Appl. Phys.* 98,073301 (2005).
- [6] E. Fisher, *I. Appl. Phys.* 47,2954 (1976).
- [7] W.W. Stoffels, P.C.M. Kemps, J. Beckers, G.M.W. Kroesen, M. Haverlag. *Appl. Phys. Lett.* 87,241501 (2005).
- [8] T. Nimalasuriya, A.J. Flikweert, M. Haverlag, P. Kemps, G.M.W. Kroesen, W.W. Stoffels, J.A.M. van der Mullen, *I. Phys. D. Appl. Phys.* 39,2993 (2006).
- [9] A. J. Flikweert, M. van Kemenade, T. Nimalasuriya, M. Haverlag, G.M.W. Kroesen, W.W. Stoffels, *J. Phys. D. Appl. Phys.* 39,1599 (2006).