# LIFETIME REVIEW ANALYSIS FOR METAL HAILDE LAMPS USING FINITE ELEMENT METHOD

**Aniruddha Mukherjee[1], Pallavi Malik[2]***

**Abstract**
Metal halide lamps comes under the category of high intensity discharge lamps which involves high intensity thermal plasma discharge phenomenon. The plasma discharge in MH lamps are different from other plasma discharge by the following characteristics: (a) the velocity of all the discharge obeys Maxwellian distribution (b) the excited energy states are occupied by Boltzmann distribution (c) composition of the plasma can be derived from local chemical equilibrium. This paper explores the temperature distribution and the immediate effects towards the life of Metal Halide lamp. The temperature profile for the Metal Halide lamp is numerically investigated. MH lamps are known to operate in two distinct modes depending upon the cathode electric field, namely – hot spot mode and diffuse mode. These two modes are basically two different modes of arc attachment of the electrodes. Since electrode plays a significant role influencing MH lamp life it becomes imperative to understand the electrodes. In this context the energy balance equation are taken into consideration. The equations are solved using Finite Element Method. The necessary boundary condition for solution of the equation is the plasma boundary layer for the cathode heat conduction. The analysis provides the temperature distribution inside the lamp for different electrode geometry.

**Keywords: -** Electrodes, plasma boundary layer, radiation transport mechanism, HID lamps.

[1]Department of Electrical Engineering, University of Engineering and Management, Jaipur, Rajasthan, India. Email id: mukherjeeanirudh73@gmail.com
[2]*Department of Mathematics, University of Engineering and Management, Jaipur, Rajasthan, India.

***Corresponding author: -** Pallavi Malik
*Department of Mathematics, University of Engineering and Management, Jaipur, Rajasthan, India. Email: pallavi_malikk@rediffmail.com

## Introduction

The HID lamps are gradually being replaced by LEDs. However, one striking aspect in the case of HID lamps is its' usage as outdoor lighting particularly for sports lighting. As it has been reviewed that currently both metal halide lamps and LEDs are used in conjunction in meet the demands in sports lighting. However as evident from the experimental observations that below the life expectancy in MH lamps drop to 50% at half the rated life. This perennial problem has led to the restricted usage of MH lamps as light source where the colour rendering index alongside the high lumen output are significant parameters. It has further been observed that higher the wattage of MH lamps higher is the rate of degradation of lumen output. The degradation of light output could well be understood from the construction of the arc tube of MH lamps.

High Intensity Discharge (HID) Lamps generally adopts same life testing procedure as that of fluorescent lamps and the difference is only in terms of its standard operating cycle time. Metal Halide (MH) Lamps, which are generally used in conventional indoor lighting applications because of their good color-rendering properties, are operated in frequent switching mode and hence differs in terms of procedure required for predicting their lamp life [1].

Chanin [2] explored the impact of cataphoresis in discharge lamps particularly in low pressure sodium lamps that leads to the depletion of sodium and thus loss in efficacy. Waymouth [3] investigated that if the electron current at the anode is more than the anode current current in HID lamps then the anode would charge negatively.
Lister et al. [4] explored the influence of acceleration due to gravity on convective flows in HID lamps and suggested the Navier Stokes relation for the same. In the case of MH Lamps, they reported that performance is significantly

influenced by improper orientation during operation. Holstein, Trigt and Irons works on transport mechanism [5]-[13]. This was further substantiated by Molisch and Oehry who had also investigated the radiation transport mechanism in HID lamps [14].

Lister further explored the work on all these researchers and concluded the various aspects of fluorescent and HID lamps in relation of lamp geometry, arcing phenomenon, fluid thermodynamics, influence of gravity in arc attachment of HID lamps, characteristics of materials used inside the lamps. In a sense it is an exploration of research work on low pressure and high pressure gas discharge lamps till date [15].

Fabela et al. [16] have studied performance of High Pressure Sodium (HPS) Vapour Lamps and have suggested Electrical Cathode Model (ECM) to observe the instantaneous voltage drop and the temperature distribution inside the cathode sheath. This model can be used in order to predict the behavior of HPS vapour lamps in case of its use for longer durations. In the case of Low Pressure Sodium (LPS) Vapour lamps deposition of sodium ions inside the arc tube can be considered. While considering HID lamps it is important to consider lamps which are in vogue. Hence Mercury Vapour (MV) lamps are not considered as they have become obsolete. Amongst the HID lamps two lamps which are worthy of consideration are HPSV and MH lamps.

Louden and Schmidt [17] investigated the effect of temperature and pressure in the arc tube of HPS vapour lamps. Z. Toth and H. Lovas [18] concluded that burn orientation and metal deposition inside the arc tube are also important factors influencing the performance of MH lamps.

Corazza et.al. [19] investigated the impact of hydrogen in HID lamps and concluded that it is the most harmful element prohibiting lamp ignition. It was further suggested by the researcher that the injection of getter materials in the form of zirconium – aluminum and other rare earth alloys aids in absorption of gaseous impurities inside the arc tube of HID lamps.

Alexander et. al. [20] further explored the introduction of mercury free HID lamps, commonly referred as xenon lamps. These lamps were thoriated to reduce the work function. But posed a major economic threat pertaining to the trade and regulation of thorium. It was further explored the mode of arc attachment and its' subsequent influence of lamp life.

Van Casteren in his research work reconnoitered the influence of lamp ballast compatibility in HID lamps [21].

National Lighting Product Information program [22] and Power Electronics Technology [23] have discussed the impact of dimming of HID lamps along with their ballast control.

Other factors affecting HID lamp life include number of starts, operating voltage, ineffective control devices (ballasts, capacitors, etc.), and extremely high operating temperatures. These factors are measured directly and analysed with respect to their burning hours.

Shi et al. [24] have observed that for MH lamps the quality of input power and frequency along with the choice of ignitor can be considered to be the important parameters affecting their performance.

Waymouth [25] have explained the relationship between the emission of electrons from Cathode with that of temperature and electric field. Mackeown [26] deduced the mathematical relation between electric field and potential drop in the Cathode sheath.

Litchenberg et. al [27] investigated different modes of arc attachment, namely, - (a) spot mode (b) diffuse mode and (c) super spot mode. It was further observed that the surface structure of the electrodes is widely influenced by the different modes of arc attachment.

Flesch and Neiger [28] numerically investigated the interaction between electrodes and plasma in the case of HID lamps.

Stofells, Hout and Kroesen [29] observed the influence of gravity on the arc and concluded that the stability of the arc is hugely influenced under the presence of micro-gravity and macro gravity conditions.

This paper explores the temperature distribution and the immediate effects towards the life of HID lamp. The temperature profile for the HID lamp is numerically investigated. HID lamps are known to operate in two distinct modes depending upon the cathode electric field, namely – hot spot mode and diffuse mode. These two modes are basically two different modes of arc attachment of the electrodes. Since electrode plays a significant role influencing HID lamp life it becomes imperative to understand the electrodes. In this context the energy balance equation are taken into consideration. The equations are solved using Finite Element Analysis tool WELSIM 2.0. The necessary boundary condition for solution of the equation is the plasma boundary layer for the cathode heat conduction. The analysis provides the temperature distribution inside the lamp for different electrode geometry.

**HID Lamp Modelling**

In the case of HID lamps the set of equations used includes the basic modelling equations as discussed by Lister et al. [25]. Some of the most important equations include the Lamp Electrode Modelling.

Shi et al. [24] have presented that Lamp Electrode Temperature which has a strong influence on HID lamp lifetime. The numerical models of HID lamp electrodes considered here are:

$$W_k = I\left(V_c - (\varphi / e) + (5k_B T_k / 2e)\right) \quad (1)$$

where,

$W_k$ : Cathode Power Consumed.
$I$ : Discharge Current.
$V_c$ : Cathode Voltage.
$\Phi$ : Work Function.
$k_B$ : Boltzman's constant.
$T_k$ : Cathode Temperature.
$e$ : Charge of Electron.

and, $$W_a = I\left(V_a + (\varphi / e)\right) \quad (2)$$

where,

$W_a$ : Power absorbed by anode.
$V_a$ : Anode Voltage.

The temperature profile inside the arc tube of a HID lamp can be obtained from the ECM proposed by Fabela et al. [27] in which the Total current density (J) is related with the temperature of the active surface of the cathode '$T_{act}$' by the following relation:

$$J = \left(\frac{1+\beta}{1-\gamma\beta}\right) A T_{act}^2 \exp\left\{\frac{e\varphi(E_k)}{k_B T_{act}}\right\} \quad (3)$$

here,

$\beta$ : Ratio of Ion Current Density (Ji) and Electron Current Density ($J_e$).
$\gamma$ : Ratio of Secondary Electron Emission ( $J_e^{sec}$ ) and ( $J_i$ ).
A : Richardson constant ($1.2 \times 10^6$ $Am^{-2}$ $K^{-2}$).
$E_k$ : Electric field of the cathode.
$\varphi$ ($E_k$) : Difference between the Tungsten Work Function and the Schottky
correction for the tungsten work function.

**Results and discussions**

The solutions to the equations (4), (5), and (6) were carried out through WELSIM 2.0, a finite element software package for simulating welding processes. The results of the simulations are shown in Figures 1 and 2. Figure 1 shows the temperature distribution on the active surface of the cathode at the beginning of operation. The temperature is highest at the center of the cathode and decreases towards the edges. The temperature distribution is relatively uniform. Figure 2 shows the temperature distribution on the active surface of the cathode after 1000 burning hours. The temperature is still highest at the center of the cathode, but it has increased overall. The temperature distribution is also less uniform, with some hot spots near the edges. The results of the simulations show that the temperature of the cathode increases over time. This is because the cathode is subjected to heat from the arc. The increase in temperature can lead to a few problems, such as arc instability and premature failure of the lamp. The results of the simulations can be used to improve the design of metal halide lamps. By understanding how the temperature of the cathode changes over time, engineers can design lamps that are more stable and have a longer life. The temperature distribution on the cathode is affected by a number of factors, including the arc current, the type of gas used in the lamp, and the ambient temperature. The increase in temperature can also lead to other problems, such as the evaporation of the cathode material and the deposition of metal halide salts on the cathode. There are several ways to reduce the temperature of the cathode, such as using a different type of gas or using a more efficient lamp design.

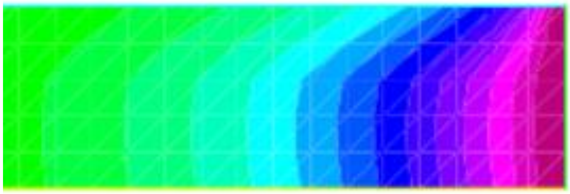

**Fig.1.** Temperature variations across the electrode at starting

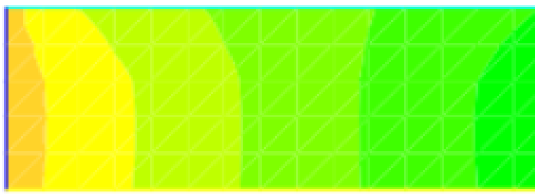

**Fig.2.** Temperature variation after 1000 burning hours.

The radiation transport mechanism of HID lamps plays a pivotal role in determining the life of these lamps. The temperature distribution inside the lamp is important, as well as the ratio between electric field to gas number density. If the vapour pressure is too high after the lamp is turned off, the lamp will fail to restart. This is because the radiation transport mechanism is disrupted, and the lamp cannot heat up enough to restrike. The energy balance equation is also important, as it determines how much energy is lost to radiation. This loss of energy can shorten the life of the lamp, as it means that the lamp has to work harder to maintain its temperature. Overall, the radiation transport mechanism is a key factor in determining the life of HID lamps. Other factors, such as the electrode geometry and the vapour pressure, also play a role, but the radiation transport mechanism is the most important. Here are some specific points to emphasize:

- The radiation transport mechanism is responsible for the temperature distribution inside the lamp.
- The ratio between electric field to gas number density also affects the temperature distribution.
- If the vapour pressure is too high after the lamp is turned off, the lamp will fail to restart.
- The energy balance equation determines how much energy is lost to radiation.
- The radiation transport mechanism is the most important factor in determining the life of HID lamps.

The fundamental equations for the same may be referred as hereunder:

$$-\nabla.(\varepsilon\nabla\phi)=\sum_{j=1}^{n}q_jN_j+\rho \qquad (4)$$

$$\frac{\partial N_i}{\partial t}=-\nabla.\left(-D_i\nabla N_i+\frac{q_i}{|q_i|}\mu_iN_i\nabla\phi\right)+S_i=-\nabla.\phi_i+S_i$$
(5)

$$\frac{\partial\rho}{\partial \mathrm{t}}=\left[\sum_{j=1}^{n}q_j\left[-\nabla.\varphi_j+S_j\right]-\nabla.[\sigma(-\nabla\varphi)]\right] \qquad (6)$$

Here the parameters is defined as follows:
ε: Permittivity in F/m
φ: Electric potential in V/m
q: Elementary charge in C
N: Species number density
ρ: Charge density in $C/m^2$
D: Diffusion coefficient
µ: Mobility
S: Source function due to collisions
σ: Conductivity in Siemens

The equations (4), (5), and (6) are important for understanding the breakdown phenomenon in metal halide lamps. These equations describe the electric field, the electron density, and the ion density in the lamp, respectively. The solution to these equations can provide insight into how the breakdown voltage is affected by the lamp's geometry, the type of gas used in the lamp, and the presence of a penning mixture. The penning mixture is a combination of gases that can help to reduce the breakdown voltage in metal halide lamps. This is because the penning mixture can create a more favorable environment for the ionization of electrons. The solution to the equations (4), (5), and (6) can help to determine the optimal composition of the penning mixture for a given lamp geometry. The solutions of the equations (4), (5), and (6) for different lamp geometries can also provide insight into the lamp life. This is because the breakdown voltage is a key factor in determining the lamp life. A lower breakdown voltage means that the lamp is more likely to start up, and it also means that the lamp is less likely to fail prematurely. The work done by Brian Lay et. al. [30] provides detailed insight into the equations (4)-(6). This work shows how the equations can be solved using the finite element method. The finite element method is a numerical method that can be used to solve a wide variety of problems. It is a powerful tool for understanding the breakdown phenomenon in metal halide lamps.

**Conclusion**

The surface temperature of a lamp's electrodes is a key factor in determining the life of the lamp. As the lamp ages, the surface temperature of the electrodes increases. This is because the electrodes become less efficient at conducting heat away from the arc, and the arc itself becomes hotter.

The increased surface temperature of the electrodes leads to a number of problems. First, it can cause the electrodes to erode more quickly. This shortens the life of the lamp. Second, the increased surface temperature can cause the lamp's color rendering index (CRI) to decrease. The CRI is a measure of how well a lamp renders the colors of objects. A lower CRI means that the lamp will make objects look less natural. In outdoor applications, such as sports and horticultural lighting, a high CRI is important. This is because the CRI helps to ensure that the colors of objects are rendered accurately. A low CRI can make it difficult to see objects in outdoor lighting, and it can also make objects look unnatural. Therefore, the surface temperature of a lamp's electrodes is a key factor in determining the life of the lamp, and that it can also affect the lamp's CRI. This is important to consider when choosing a lamp for outdoor applications. The surface temperature of the electrodes is determined by several factors, including the lamp's design, the type of gas used in the lamp, and the ambient temperature. The increased surface temperature of the electrodes can also lead to other problems, such as arc instability and premature failure of the lamp.

There are a few ways to reduce the surface temperature of the electrodes, such as using a different type of gas or using a more efficient lamp design.

**References**


1. National Lighting Product Information Program, "Lighting Answers," vol. 9, issue 1, June 2006 [Online]. Available www.lrc.rpi.edu/ programs/ nlpip/ lightinganswers/t8.
2. Chanin, L. M., in *Gaseous Electronics* edited by Merle N. Hirsh and H. J. Oskam (Academic, New York), Vol. 1, p. 133, 1978.
3. Waymouth. J. F., pp.1-353, *Electric Discharge Lamps* (MIT, Cambridge, MA), 1971.
4. Holstein, T., 1947, Phys. Rev. 72, 1212.
5. Holstein, T., 1951, Phys. Rev. 83, 1159.
6. Irons, F. E., 1979a, Journal of Quantitative Spectroscopy and Radiative Transfer 22, 1.
7. Irons, F. E., 1979b, Journal of Quantitative Spectroscopy and Radiative Transfer 22, 21.
8. Irons, F. E., 1979c, Journal of Quantitative Spectroscopy and Radiative Transfer 22, 37.
9. Van Trigt, C., 1969, Physics Reviews 181, 97.
10. Van Trigt, C., 1970, Physics Reviews A 1, 1298.
11. Van Trigt, C., 1971, Physics Reviews A 4, 1303.
12. Van Trigt, C., 1976a, Physics Reviews A 13, 726.
13. Van Trigt, C., 1976b, Physics Reviews A 13, 734.
14. Molisch, A. F., and B. P. Oehry, "*Radiation Trapping in Atomic Vapours,"* Clarendon, Oxford, 1998.
15. G. G. Lister, J. E. Lawler, W. V. Lapatovich and V. A. Godyak, "The physics of discharge lamps", *Reviews of Modern Physics*, vol. 76, pp. 541-598, April 2004.
16. J. L. T. Fabela, J. O. Pacheco-Sotelo, M. Pacheco, J. S. Benítez-Read, R. López-Callejas, G. Zissis and S. Bhosle, "Modelling the voltage drop across the Cathode sheath in HPS", *IEEE Transactions on Plasma Science*, vol. 35, no. 4, pp. 1104 - 1110, August 2007.
17. W.C. Louden and K. Schmidt, "High Pressure sodium discharge arc lamps", *Journal Illuminating Engineering* Society, vol.49, pp. 696-702, December 1966.
18. Z. Toth, H. Lovas, "Chemistry of materials science phenomena in high intensity discharge light sources," *Pure and Applied* Chemistry, vol. 79, no.10, pp. 1771-1778, September2007.
19. A. Corazza, A. Giorgi, C. Boffito, V. Massaro and D. Caccia, "Characteristics of the getter materials in high intensity discharge lamps," *IEEE Annual Industry Applications Conference,* pp. 1801-1807, Tampa, FL, 2006.
20. Alexander Alexejev, Peter Flesch, Jurgen Mentel and Peter Awakowicz, "*Change of the arc attachment mode and its effect on the lifetime in automotive high intensity discharge lamps*," Journal of Applied Physics, 120, 133301, 2016.
21. Van Casteren, D.H.J., "*Electronic operation and control of high intensity gas discharge lamps*," PhD thesis, 2012.
22. National Lighting Product Information program, "Dimming Systems for high Intensity discharge lamps", vol.1, no. 4, September 1994 [Online]. Available www.lrc.rpi.edu/programs/LAHID.pdf.
23. *Power Electronics Technology*, "Shedding light on HID ballast control," [Online]. Available www.powerelectronics.com.
24. S. Shi, W. Li, W. Zhang, S. Zhang, "Effects of frequency & current on the electrode temperature of HID lamps", *Consumer Electronics, Communications and Networks, CECNet 2012,* Yichang, pp. 1010-1013, 21-23 April 2012.
25. J. F. Waymouth, "Analysis of Cathode-spot behavior in high-pressure discharge lamps," *Journal of Light and Visual Environment*, vol. 6, no. 2, pp. 53-64, January 1982.
26. S. S.Mackeown, "The Cathode drop in an electric arc," *Physics Review*, vol. 34, no. 4, pp. 611–614, August 1929.
27. S. Litchenberg et.al., "Observation of different modes of cathodic arc attachment to HID electrodes in a model lamp," Journal of Physics D:Applied Physics, pp.1648-1656, 35, 2002.
28. P. Flesch and M. Neiger, "Numerical Investigation of time dependent electrode plasma interaction in commercial HID lamps", *IEEE Transactions on Plasma Science*, vol. 33 no. 2, pp. 508-509, April 2005.
29. W. Stofells, F. Hout and G. Kroesen, "Helical instability in metal halide lamps under micro and hypergravity conditions," Applied Physics Letters, pp.1-3, 88, 091502, 2006.
30. Brian Lay, R. Moss, S. Rauf, M. Kushner, "Breakdown processes in metal halide lamps", Plasma Sources Science and Technology, IOP Science, pp.8-21, 12, 2003.