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REVIEW ARTICLE

UHP lamp systems for projection applications

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Abstract
Projection systems have found widespread use in conference rooms and other professional applications during the last decade and are now entering the home TV market at a considerable pace. Projectors as small as about one litre are able to deliver several thousand screen lumens and are, with a system efficacy of over 10 lm W^{-1}, the most efficient display systems realized today. Short arc lamps are a key component for projection systems of the highest efficiency for small-size projection displays.

The introduction of the ultra high performance (UHP) lamp system by Philips in 1995 can be identified as one of the key enablers of the commercial success of projection systems. The UHP lamp concept features outstanding arc luminance, a well suited spectrum, long life and excellent lumen maintenance. For the first time it combines a very high pressure mercury discharge lamp with extremely short and stable arc gap with a regenerative chemical cycle keeping the discharge walls free from blackening, leading to lifetimes of over 10 000 h.

Since the introduction of the UHP lamp system, many important new technology improvements have been realized: burner designs for higher lamp power, advanced ignition systems, miniaturized electronic drivers and innovative reflector concepts. These achievements enabled the impressive increase of projector light output, a remarkable reduction in projector size and even higher optical efficiency in projection systems during the last years.

In this paper the concept of the UHP lamp system is described, followed by a discussion of the technological evolution the UHP lamp has undergone so far. Last, but not least, the important improvements of the UHP lamp system including the electronic driver and the reflector are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Large screen projection systems became increasingly popular during the last decade. The business developed rapidly and growth is expected to continue to be high, as shown in figure 1. Looking back, the introduction of the ultra high performance (UHP) lamp concept by Philips in 1995 [1–4] was a significant technological breakthrough for the projection market and can be identified as one of the key enablers of the commercial success of projection systems. Following its launch, the UHP lamp system has been improved with a fast innovation rate [5, 8–10, 12, 14, 19, 20, 22–24]. UHP lamps today are the standard for most commercially available front and rear projectors and have replaced the previously used metal halide lamps.

About ten years ago, the performance of liquid crystal display (LCD) projectors was rather poor: a 46 litre size, 21 kg projector delivered just 400 screen lumens with VGA

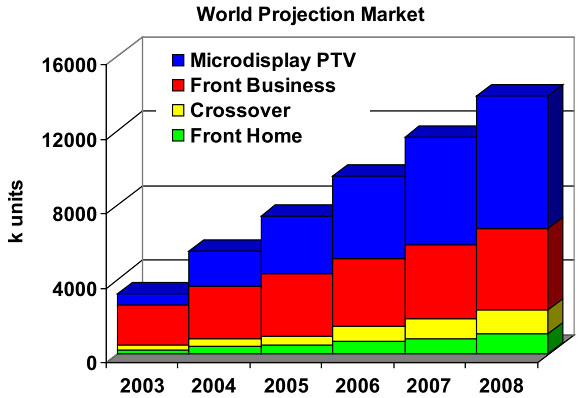

Figure 1. World projection market according to Techno Systems Research.

Figure 2. Ultra-portable projector with UHP lamp (InFocus).

Figure 3. Rear projection TV with UHP lamp (RCA).

resolution. Today, projectors of one-tenth that size can create high-quality XGA pictures with more than 3000 screen lumens brightness with a single UHP 200 W lamp. On the other end of the product spectrum, ultra-portable projectors (see figure 2) of 1 kg weight and less than 1 litre volume enable a bright XGA presentation with more than 1000 screen lumens.

Front projectors—now commonly called 'beamers'—have found their place in almost each meeting room during the last ten years. In the last few years also, rear projection TV sets (see figure 3) have become important in the market and sales are growing rapidly.

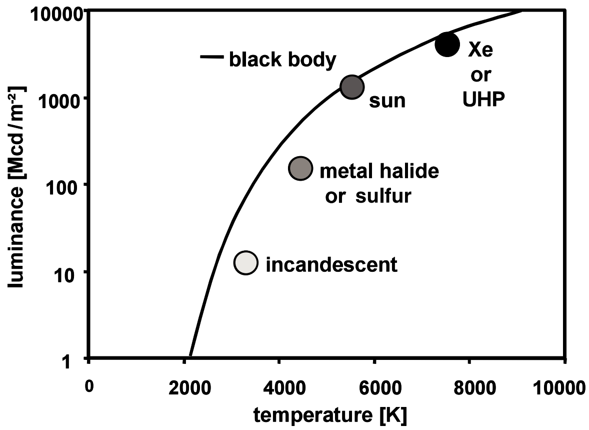

Figure 4. Luminance of light sources compared with the black body radiator luminance.

Short arc lamps are a key component for projection systems for achieving the highest efficiency for small projection display sizes. Projection is a very demanding application for the lamp. The light source should be point-like, provide extremely high brightness, high total light flux and a white spectrum. Besides, high demands on lamp efficiency and lifetime have to be fulfilled.

Further progress in both displays and optics increases the optical demands to be fulfilled by the light source. The innovation speed therefore depends on the availability of improved light sources with smaller size and even shorter arc length.

2. The concept of the UHP lamp

2.1. A pure mercury discharge for highest luminance

For highly efficient projection systems the arc luminance should be as high as possible. With today's small display sizes, an average luminance of above 1 Gcd m^{-2} is needed. The maximum luminance $L(T)$ that can be reached in thermal equilibrium is physically linked to the discharge temperature by the well-known Planck's law:

$$L(T) = k \cdot \int V(\lambda) \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/kT\lambda} - 1} d\lambda. \qquad (1)$$

Here, k is the Boltzmann constant, λ is the wavelength of emitted light, $V(\lambda)$ is the wavelength sensitivity curve of the human eye, h is the Planck constant, c the speed of light and T the radiator temperature.

Metal halide additives that are used in many lamp types for improving the colour properties of the lamp spectrum mostly reduce the arc temperature owing to their comparably low ionization potential. This leads to a lower luminance of the arc and hence does not make metal halide lamps ideal for projection. A high luminance (see figure 4) can only be reached by rare gas and pure mercury discharges, as used in the UHP lamp. A pure mercury discharge, however, is superior to rare gas discharges in luminous efficiency while reaching the same luminance.

The UHP lamp follows this approach and contains only mercury as radiating species. UHP lamps typically reach an average arc luminance well above 1 Gcd m^{-2} and are, in that respect, an ideal light source for projection applications.

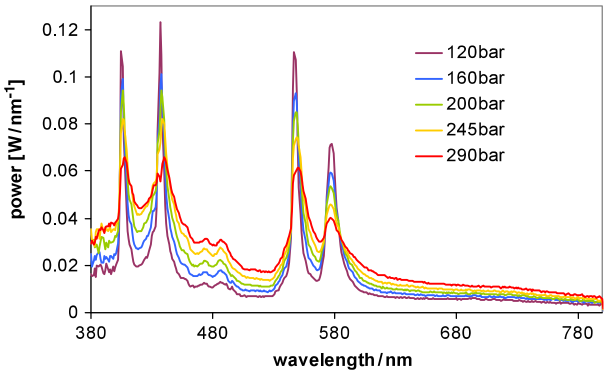

Figure 5. UHP Spectra for different mercury pressure, an arc gap of 1 mm measured at 120 W and through an aperture representing an optical system etendue of $E = 10\,mm^2$ ster. This figure is best viewed in colour in the online edition. The 120 bar curve is the highest in the peaks and the lowest between peaks; the 290 bar curve is the lowest in the peaks and the highest between the peaks.

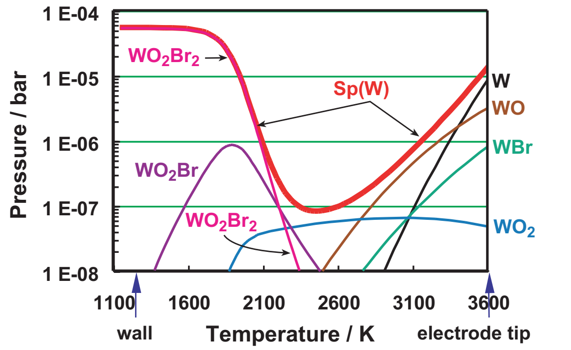

Figure 6. Principle of regenerative cycle: typical gas phase composition of a UHP lamp as a function of temperature. Sp(W) is the sum of saturation pressures of all tungsten containing species.

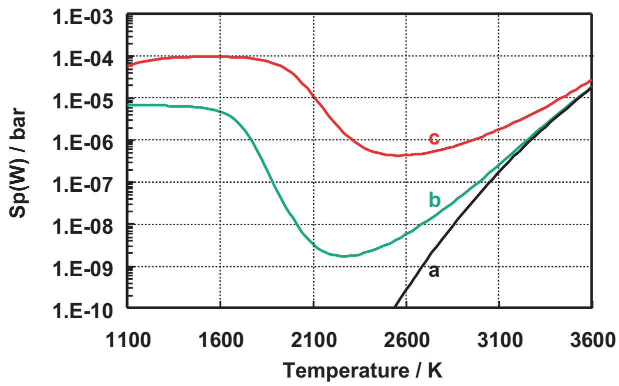

Figure 7. Schematic view of the summed tungsten pressure Sp(W) as a function of temperature for different bromine levels (curves a, b, c are explained in the text).

2.2. High pressure for continuous spectrum

For an efficient projection system the spectral properties of the light source are at least of the same importance as the lamp luminance. Filters are typically used for colour matching and for rebalancing white. With an UHP lamp, the efficiency of this colour matching and rebalancing is typically 25% for a single-panel, sequential colour device and 70% for a three-panel projector. In any case, light is lost by this filtering. To reduce these losses the lamp should exhibit an even distribution of the spectral contributions between red, green and blue.

Figure 5 shows spectra for various lamp pressures measured through an aperture (for details see section 2.7) representing the usable light in a typical optical system of a modern projector. It can be clearly seen that for mercury pressures above 200 bar more light is emitted in the continuum radiation than in the atomic spectral lines. Especially, the important red light contribution above 600 nm strongly depends on the lamp pressure. The more even distribution of the emitted light over the wavelength range is directly related to a higher colour balancing and therefore to the projector efficiency. For good colour balancing in projection systems it is essential to realize ultra high lamp pressures.

2.3. Regenerative cycle for long life

The lifetime of UHP lamps can exceed 10 000 h by far. This is realized for the first time in a commercial HID lamp by a so-called regenerative chemical transport cycle using a halogen filling [1].

As principally known from halogen incandescent lamps, in the presence of halogen and oxygen (O_2 level fixed by the tungsten oxide temperature) evaporated tungsten material can be transformed near the relatively cold discharge vessel wall into stable ternary tungsten compounds, e.g. WO_2X_2 ($X =$ halogen), see figure 6.

In the hotter regions close to the lamp electrodes the oxy-halide molecules are decomposed. By these chemical transport processes, tungsten atoms are brought back to the lamp electrodes in a regenerative manner. This cycle prevents, or at least considerably reduces, wall blackening caused by the evaporation of tungsten from the electrodes.

The direction and magnitude of tungsten transport strongly depend on the effective vapour pressure of tungsten, i.e. on the sum of saturation pressures of all tungsten-containing species for a given halogen and oxygen concentration. Figure 7 shows the summed tungsten pressure Sp(W) as a function of temperature for three bromine levels:

(a) Without or with insufficient bromine, Sp(W) at the wall will remain at an extremely low level ($<10^{-20}$ bar); thus only material transports from hot to cold sites will occur causing massive blackening with no chance of tungsten recovery from the wall.
(b) With sufficient bromine (in the order of 10^{-4} bar), Sp(W) at the wall will exceed Sp(W) at hotter sites of the electrode enabling chemical transport of tungsten from cold to hot sites (i.e. from wall towards electrodes).
(c) With excess of bromine, the chemical cycle will still work, but at enhanced transport rates. Especially at the electrode feed-through with temperatures around 1800 K, chemical attack of the electrode rod can occur (see figure 8) which will lead to early lamp failure. This effect is strongly enhanced if larger amounts of gaseous impurities (H_2, H_2O, CO, CO_2) are present (for details see discussion in [6]).

The fruit of all these efforts is lamps with exceptionally long lifetimes and good maintenance, as shown in figure 9. The integral lumens remain nearly constant for more than 10 000 h

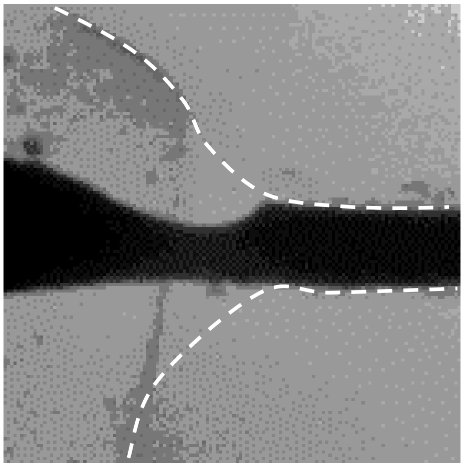

Figure 8. X ray of the electrode rod with chemical attack by too much bromine. The inner bulb contour is indicated by the white dashed lines.

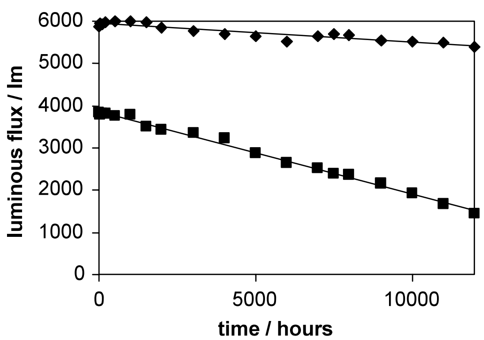

Figure 9. Light output versus burning time of an UHP 100 W lamp, 1 mm arc gap, operated in a hot environment of 250˚C. (♦) integrated luminous flux, (■) luminous flux collected in a typical projector system.

owing to the halogen transport cycle. A breakdown of the chemical cycle, however, would lead to strong blackening, resulting in an overheating of the bulb and a very fast end of life. The collected lumens drop over life under the present experimental conditions. This is a consequence of electrode burn back and whitening of the bulb.

In the past years, the continuous demand for ever higher brightness was satisfied by increasing lamp powers. The higher power loads lead to a decrease in the lifetime of these lamps to about 2000 h, which is a good compromise for professional applications. For the consumer market (cf figure 1), a longer lamp life becomes a key requirement again. We also see a trend where the size of micro-display projection TV (MD-PTV) is shifting towards screen diagonals >50 inches. This asks for a combination of longest life and high brightness and challenges the design of new UHP lamp generations.

2.4. Burner models

The design of higher power UHP lamps—while keeping the arc short—is guided by advanced lamp models [7, 21], which include the plasma, the plasma–electrode interaction and the thermal balance of the lamp envelope. This allows for a proper design of lamps operating close to the limits of the bulb and electrode materials.

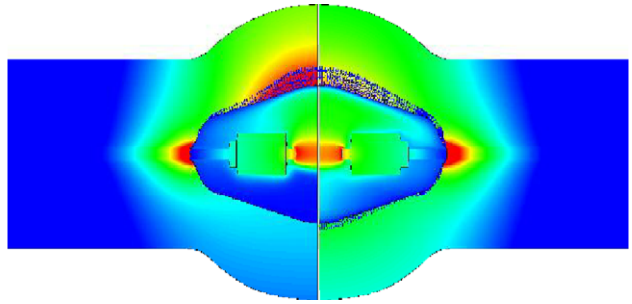

Figure 10. Temperature of plasma and quartz bulb, calculated with (right) an without (left) inclusion of radiative transfer. Please note that the same colour coding is used for the space inside the lamp and for the bulb, but the real temperature scale is largely different.

The performance of UHP lamps is determined largely by the temperatures on the inside of the burner. The Hg pressure inside the lamp has to be higher than 200 bar to allow for good colour quality and high efficiency. This requires bulb temperatures above 1190 K at the coldest spot inside the lamp. At the same time the hottest parts of the quartz envelope have to stay cold enough (<1400 K) to resist the high pressure without deformation and to stay clear without any recrystallization. A sophisticated burner design is necessary to keep the temperature differences within these limits.

Especially for a long life product, the temperature differences should be as small as possible. Owing to the strong convective energy transport in the lamp plasma, the temperature at the upper wall is considerably higher than that at the lower wall.

Because the crucial temperatures on the inside cannot be measured directly, a thermal model is required for lamp design. A model of the lamp plasma is needed to predict the distribution of the thermal flux that heats the wall. The plasma model has to include heat transport owing to thermal conduction, convection and radiative transfer.

The calculation of radiative transfer requires an enormous numerical effort, but is inevitable, because its neglect leads to wrong temperature profiles of the plasma and the [21, 27], as is shown in figure 10. The left-hand side shows the result of a model calculation without radiative transfer, while the right-hand side is based on a model including radiative transfer. As can be clearly seen, radiative transfer leads to a reduction of the top–bottom asymmetry introduced by convection. Both the plasma temperature distribution and the bulb temperature distribution show much smaller deviations between top and bottom when radiative transfer is included in the plasma model. In figure 11 the comparison with a spectroscopic measurement of the plasma temperature demonstrates the quality of the model.

2.5. Electrical properties

The burning voltage of a UHP lamp can be described by

$$U_{\text{lamp}} = U_{\text{elec}} + U_{\text{arc}} = U_{\text{elec}} + a \cdot ed \cdot p_{\text{Hg}}, \qquad (2)$$

where U_{elec} is the voltage drop at the electrodes, i.e. the sum of cathode and anode fall voltages, *ed* the electrode distance or arc gap, p_{Hg} the pressure and a is a constant. The higher

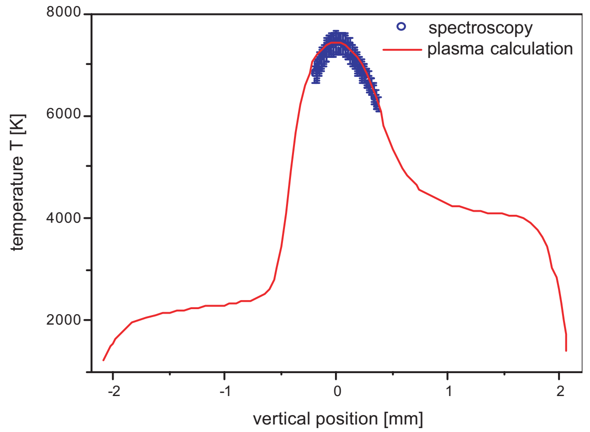

Figure 11. Plasma temperature as a function of vertical coordinates in the mid-plane as measured by plasma spectroscopy and calculated for a 120 W UHP burner.

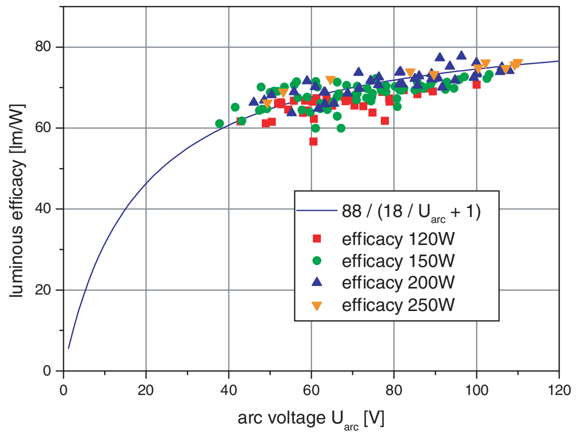

Figure 13. Luminous efficacy of UHP lamps as a function of arc voltage for research lamps operated at lamp powers between 120 and 250 W. The solid line is calculated from equation (3).

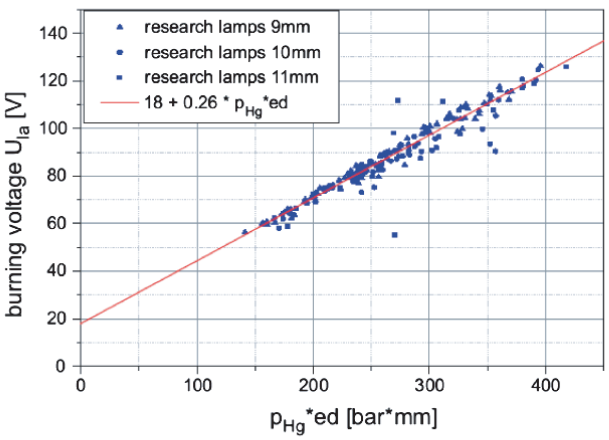

Figure 12. Burning voltage of UHP lamps as a function of the product of mercury pressure and electrode distance.

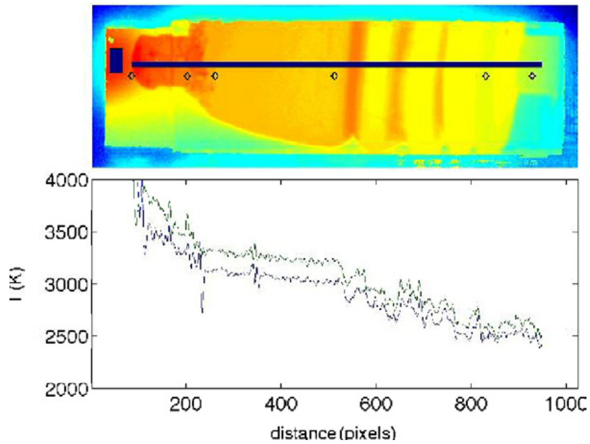

Figure 14. Measured temperature along a UHP electrode (250 W, 1.3 mm), at full operation (green) and dimmed operation (200 W, blue).

the burning voltage, the smaller is the relative contribution of the electrode losses, and a higher lamp efficacy will result. However, with decreasing arc length, the voltage drop over the arc is reduced and, relative to the total input power, the electrode losses become more important.

UHP lamps show a clear linear dependence of the burning voltage on the mercury pressure p_{Hg} [26]. This is shown in figure 12 for three different types of burners designed for different lamp powers, the larger burners being used for higher power. All the lamps used here were research samples, where a large variation in electrode distance and pressure was possible.

From figure 12 the electrode fall voltage $U_c = 18$ V and the slope $a = 0.26\,\mathrm{V\,mm^{-1}\,bar^{-1}}$ can be determined. With these two parameters, the electrical efficiency of UHP lamps can be written as:

$$\varepsilon_{el} = \frac{P_{arc}}{P_{lamp}} = \frac{U_{arc}}{U_{arc} + U_c} = \left[1 + \frac{69.2}{p_{Hg} \cdot ed}\right]^{-1}, \qquad (3)$$

where p_{Hg} is in bar and ed in millimetres. As an example, for a UHP lamp with $p_{Hg} = 200$ bar and $ed = 1$ mm, the electrical efficiency is $\varepsilon_{el} = 0.74$.

The burners from the lamps shown in figure 12 were measured in an integrating sphere. From the total emitted light flux we could then determine the radiation efficacy of the arc plasma, using equation (3). The result is shown in figure 13.

The straight line is fitted to the experimental results with the plasma efficacy $\eta_{plasma} = 88\,\mathrm{lm\,W^{-1}}$ as a fit parameter. The plasma efficacy is slightly dependent on the power on which the lamp was operated: for higher powers, it is slightly higher than for the same burners operated at lower powers.

2.6. Electrode design

A long-life lamp requires electrodes with a very stable shape: the electrode tip should not recede (burn-back) or move laterally, owing to evaporation and transport of tungsten. These phenomena depend mainly on the temperature of the electrode [24,27]. Therefore, long-life electrode design aims at controlling electrode temperature. The optimum temperature distribution features a moderately hot electrode body (for little burn-back but sufficient cooling by radiation) and a hot tip (for a stable arc attachment).

More detailed criteria can be deduced from systematic life tests of lamps with known electrode temperatures, flanked by model simulations [24]. Figure 14 shows the

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