6. High Pressure Discharge Lamps

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### 6.1 Overview of Low- and High-Pressure Discharge Lamps

<table>
<thead>
<tr>
<th>Low-Pressure Lamps</th>
<th>High-Pressure Lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg low-pressure (TL)</td>
<td>Hg high-pressure (HPMV = high pressure metal vapour)</td>
</tr>
<tr>
<td>Hg low-pressure (CFL)</td>
<td>Na high-pressure (HPS = high pressure sod.)</td>
</tr>
<tr>
<td>Na low-pressure (SOX)</td>
<td>Metal-halide high-pressure (MH)</td>
</tr>
</tbody>
</table>

**HID = High Intensity Discharge**
6.2 Spectrum of Hg Discharges

Energy level scheme of Hg

Ionization level (~ 10.4 eV)

Schematic emission spectrum of a Hg-discharge at a low pressure [~ mbar]

Level energy [eV]

λ [nm]

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6.2 Spectrum of Hg Discharges

Pressure dependence of the lumen output

60 lm/W ⇒ Why is this of interest for lamps?

Good imaging properties
High luminance

Pressure increase

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6.2 Spectrum of Hg Discharges

Measured spectra of water-cooled capillary mercury discharge lamps

Source: W. Elenbaas, Quecksilberdampf-Hochdrucklampen (1966)
6.3 The High-Pressure Mercury Lamp (HP)

- Evacuated outer bulb
- Melting Electrode
- Burner (Hg, noble gas = starting Gas, mostly Xe)

Ballast
6.4 Phosphors for High-Pressure Mercury Lamps

Blue-white light due to the lack of red radiation in the emission spectrum
Solution: Phosphor!

η = 60 lm/W
R_a = 20
Lifetime = 20,000 h
6.4 Phosphors for High-Pressure Mercury Lamps

Suitable phosphors:
- \((\text{Sr}, \text{Mg})_3(\text{PO}_4)_2:\text{Sn}\)
- \(\text{Mg}_4\text{GeO}_{5.5}\text{F}:\text{Mn}\)
- \(\text{YVO}_4:\text{Eu}\)
- \(\text{Y(V, P)O}_4:\text{Eu}\)

\[\eta = 60 \text{ lm/W}\]
\[R_a = 50\]
\[\text{Lifetime} = 20,000 \text{ h}\]
6.4 Phosphors for High-Pressure Mercury Lamps

**Sn²⁺, Mn⁴⁺ phosphors** as UV → Red converter

Luminescence spectra of (Sr,Mg)₃(PO₄)₂:Sn

- \( \lambda_{\text{max}} = 620 \text{ nm} \)
- \( \text{QE}_{254} = 79 \% \)
- \( \text{RQ}_{254} = 5 \% \)
- \( x = 0.549 \)
- \( y = 0.426 \)
- \( \text{LE} = 150 \text{ lm/W} \)

Luminescence spectra of Mg₄GeO₅.₅F:Mn

- \( \lambda_{\text{max}} = 658 \text{ nm} \)
- \( \text{QE}_{254} = 81 \% \)
- \( \text{RQ}_{254} = 7 \% \)
- \( x = 0.713 \)
- \( y = 0.287 \)
- \( \text{LE} = 80 \text{ lm/W} \)

Problem: Low lumen equivalent of these phosphors

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6.4 Phosphors for High-Pressure Mercury Lamps

**YVO₄:Eu³⁺ phosphors - Thermal behavior**

Excitation spectra of YVO₄:Eu

![Excitation spectra graph]

Emission spectra of YVO₄:Eu

![Emission spectra graph]

Luminescence intensity as a function of temperature and excitation wavelength

![Luminescence intensity graph]

The luminous efficacy under UV-A excitation increases up to about 300 °C

Reason: Increase in spectral overlap
6.5 The Electrode

**Hg low-pressure**

- 1.0 cm
- 36 W
- \( I = 0.36 \, \text{A} \)
- Tungsten + emitter
- BaO / SrO / CaO
- \( T = 1350 \, \text{K} \)

**Hg high-pressure**

- 0.5 cm
- 400 W
- \( I = 4 \, \text{A} \)
- Tungsten + emitter
- BaO / SrO / \( \text{Y}_2\text{O}_3 / \text{ThO}_2 \)
- \( T = 2000 - 3000 \, \text{K} \)
6.6 The Electrode Feedthrough

Problem: Different thermal expansion coefficients

- Quartz (1000 °C)
- Plasma
- Tungsten
- Very thin Mo- or Nb-foil
- Molybdenum

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Expansion Coefficient</th>
<th>K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>α = 0.5*10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>α = 4.3*10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>α = 2.8*10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>
6.7 Types of Reflectors

Parabolic reflectors

Elliptical reflectors

Focal point (light source)

An ellipse has two focal points

Only when the light source is point like

HID-lamps

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6.8 Application of HP-Lamps

In street lighting (outdoor lighting)

\[ \eta = 60 \text{ lm/W} \]
\[ \text{Ra} = 50 \]
\[ \text{Lifetime} = 20,000 \text{ h} \]
\[ P = 100 \text{ W} - 2000 \text{ W} \]
6.9 The High-Pressure Sodium Lamp (HPS)

Pressure dependence of the lumen output

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6.9 The High-Pressure Sodium Lamp (HPS)

Problem: Na reacts at high temperatures with the quartz glass wall

\[ 4 \text{Na} + \text{SiO}_2 \rightarrow 2 \text{Na}_2\text{O} + \text{Si} \]

Solution: Transparent, high temperature resistant material, which does not react with Na

\( \text{Al}_2\text{O}_3 \)-ceramics (corundum): MgO, CaO, B\(_2\)O\(_3\)-Additives (DSA = densely sintered alumina)

Polycrystalline structure

Pressure, 1200 °C

Nb or Mo

Crystal

20 μm

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6.9 The High-Pressure Sodium Lamp (HPS)

Widening of the Na-line and self-absorption leads to a spectral hole in the emission spectrum at around 589 nm

$p_{Na} = 150$ mbar (saturated)

$p_{Hg} = 1000$ mbar (buffer gas)

$p_{Xe} = 100$ mbar (start gas)

$\eta = 90 - 120$ lm/W

$R_a = 20 – 50$ (pressure dependent)

$T_c = 1930$ K

(589 + x) nm (red-shift)

(589 - x) nm (blue-shift)
6.10 Application of HPS Lamps

Architectural and street lighting
6.11 Metal-Halide High-Pressure Lamps

Filling: NaI - TlI - InI
SnBr$_2$ - SnI$_2$
NaI - DyI$_3$ (SSTV)
NaI - ScI$_3$ (automobile headlight)

Goal: High $\eta$ & color rendering
6.11 Metal-Halide High-Pressure Lamps

HPI (High Pressure Iodide) lamps

- 451 nm (In)
- 535 nm (Tl)
- 589 nm (Na)
6.11 Metal-Halide High-Pressure Lamps

Hg / NaI / TlI / DyI₃ / Ar

P = 75 W

Pₚₐ₅ / P ≈ 60 %
Pₚₐ₅,vis / P ≈ 33 %

Spectrum of a MH lamp

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Filling of metal halide lamps

Lamp starting (starting gas)
Noble gases: Ar or Xe (xenon lamps) → Penning-effect
Radioactive substances: $^{85}$Kr, $^{147}$Pm

Operating voltage
• Hg
• Trend towards the substitution of Hg (environmental aspect) → Zn

Light emission
• Hg
• Me-halides (Me = Na, In, Tl, Sc, Sn, Dy, ...)

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### 6.12 Photometric Data in Comparison

<table>
<thead>
<tr>
<th></th>
<th>Improvement</th>
<th>(\eta) (lm/W)</th>
<th>(R_a)</th>
<th>Color temperature (T_c) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HP (Hg)</strong></td>
<td>-</td>
<td>60</td>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>+ phosphor</td>
<td>60</td>
<td>50</td>
<td>3800</td>
</tr>
<tr>
<td><strong>HPS (Na)</strong></td>
<td>-</td>
<td>60 - 130</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Xe-pressure↑</td>
<td>80 - 150</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Na-pressure↑</td>
<td>60 - 90</td>
<td>60</td>
<td>2200</td>
</tr>
<tr>
<td><strong>MH</strong></td>
<td>HPI (NaI-TlI-InI)</td>
<td>70 - 80</td>
<td>70</td>
<td>3800 - 4200</td>
</tr>
<tr>
<td></td>
<td>SnBr(_2)-SnI(_2)</td>
<td>70</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NaI-DyI(_3)</td>
<td>75 - 80</td>
<td>90</td>
<td>3800 - 5600</td>
</tr>
<tr>
<td></td>
<td>NaI-ScI(_3)</td>
<td>80 - 90</td>
<td>75</td>
<td>3600 - 4200</td>
</tr>
</tbody>
</table>
6.13 Applications of MH Lamps

<table>
<thead>
<tr>
<th>MH Lamps</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPI</td>
<td>Street lighting</td>
</tr>
<tr>
<td>(NaI-TlI-InI)</td>
<td>Architectural lighting</td>
</tr>
<tr>
<td></td>
<td>Sports field lighting</td>
</tr>
<tr>
<td>Tin</td>
<td>Older type of lamp is replaced by MH</td>
</tr>
<tr>
<td>NaI-DyI₃</td>
<td>Sports field lighting</td>
</tr>
<tr>
<td>NaI-ScI₃</td>
<td>Shop lighting</td>
</tr>
<tr>
<td></td>
<td>Studio-stage-TV (SSTV)</td>
</tr>
<tr>
<td></td>
<td>Automotive headlights</td>
</tr>
</tbody>
</table>

NaI-ScI₃ + Hg + Xe (blue)
6.13 Applications of MH Lamps

SSTV market = Stage-Studio-TV

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6.13 Applications of MH Lamps

In the „beamer“

- Vorteile:
  - sehr große Bilder
  - kleines Volumen und Gewicht

Warum Projektion?

Heimkino

Rückwärts-Projektion

Professionelle Präsentationen

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6.13 Applications of MH Lamps

Construction of a beamer

A projector is actually a slide projector (diascope)!

In a beamer the slide is replaced by a small LCD screen or by a DMD (Digital Mirror Device)
6.13 Applications of MH Lamps

Operating principle of a LCD (Liquid Crystal Display)

LCDs are based on liquid crystals, which rotate the polarization plane of polarised light by a rotational angle $\alpha$.

- Polarizer-foil $P$
- Liquid crystal cell (with ITO)
- Analyzer foil (perpendicular to $P$)
- Pixel on for $U = 0$
- Pixel off for $U > 0$
6.14 UHP-Lamps

Requirements for light sources for projectors

• If possible punctual ⇒ A lot of light from a small volume
• High luminance (light density) ⇒ High Hg-pressure

UHP = **Ultra High Pressure** (Performance)
⇒ Approx. 200 bar Hg, electrode separation ~ 1 mm
⇒ Strong pressure-broadened lines of Hg

![Graph showing emission lines of Hg at 408 nm, 436 nm, 546 nm, and 577 nm](image)

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Components of UHP-Lamps

- DGA Brenner (P = 70 W)
- Nb
- Schmelzglas
- Mo
- W Electrode

6.14 UHP-Lamps

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6.14 UHP-Lamps

Design of UHP-lamps

- Chemical equations
  - Vapor pressure of metal halides
  - Disintegration of the metal halides in the plasma

- Temperature distribution in the plasma
  - Energy balance
  - Loss via radiation
  - Loss due to chemical energy
  - Loss due to heat

- Convection (flow)
- Heat conduction

- Convection equation = Navier-Stokes-Equation

\[
\frac{\partial^2 h}{\partial x'^2} + \frac{\partial^2 h}{\partial y'^2} = 0 \quad \text{Potential: } h = z + \frac{u}{\gamma w}
\]

- Energy balance of the electrodes and the wall

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6.14 UHP-Lamps

Temperaturbelastung des Quarzglases
Elektroden-temperatur und Belastung der Einschmelzung
6.15 New Developments

Sulfur lamp: In 1990 the first discharge lamp based on a molecular sulfur discharge ($S_4 - S_8$) was developed.

The energy coupling into the discharge takes place by means of a microwave generator (magnetron), because electrodes cannot be used.
6.15 New Developments

**Sulfur lamp: To generate a very large luminous flux**

![Sulfur lamp image]

**Typical operating parameters**
- Input power: 1.400 W
- Ball diameter: approx. 30 mm
- Luminous flux: 135000 lm
- Color temperature: 5700 K
- Starting time: 25 s
- Lifetime (lamp): 60.000 h
- Lifetime (magnetron): 20.000 h
- Light output: 95 lm/W

**Light source with extremely high light output, about 140000 lm (~ 40 fluorescent tubes) and (almost) pure-white light (emission band of S₈, …. , S₂ molecules)**

**Efficiency:** Similar to fluorescent lights (thus 90 - 100 lm/W)

**Problems:** EMC and lifetime of the microwave generator
6.15 New Developments

**Sulfur lamp: Mechanism of light generation ⇒ Emission from molecules, e.g. S₂**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy [eV]</th>
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<tbody>
<tr>
<td>S₃ + e</td>
<td>10.6</td>
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<tr>
<td>S₃⁻ + e</td>
<td>2.1</td>
</tr>
<tr>
<td>S₂ + S</td>
<td>0.8</td>
</tr>
<tr>
<td>S₂⁻ + e</td>
<td>9.36</td>
</tr>
<tr>
<td>S₂⁻ + e</td>
<td>1.67</td>
</tr>
<tr>
<td>S + S</td>
<td>4.46</td>
</tr>
<tr>
<td>S⁻ + e</td>
<td>10.36</td>
</tr>
<tr>
<td>S⁻ + e</td>
<td>2.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Products</th>
<th>ΔE[eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₂ + X</td>
<td>2S + X</td>
<td>4.46</td>
</tr>
<tr>
<td>S₂ + e</td>
<td>S₂⁺ + e + e</td>
<td>9.36</td>
</tr>
<tr>
<td>S₂⁻</td>
<td>S₂ + e</td>
<td>1.8</td>
</tr>
<tr>
<td>S + e</td>
<td>S⁺ + e + e</td>
<td>10.4</td>
</tr>
<tr>
<td>S⁻</td>
<td>S + e</td>
<td>2.0</td>
</tr>
<tr>
<td>Ar + e</td>
<td>Ar⁺ + e + e</td>
<td>15.76</td>
</tr>
</tbody>
</table>

6.15 New Developments

Substitution of Hg by Zn (e.g. in automotive headlamps)

Zn/Ar Discharge

- W_{el} = 75 W
- LE = 114 lm/W
- x = 0.228, y = 0.227
- T_c = 34000 K
- Efficacy = 20 lm/W
- \varepsilon = 0.174 W_{opt}/W_{elektr}
- R_a = 0

Zn/Ar/metal halide Discharge

- W_{el} = 75 W
- LE = 280 lm/W
- x = 0.436, y = 0.387
- T_c = 3000 K
- Efficacy = 85 lm/W
- \varepsilon = 0.33 W_{opt}/W_{elektr}
- R_a = 80

- \eta
- Energy efficiency
- R_a

\eta

Energy efficiency

R_a

Zn-Ar

20 lm/W

17%

0

Zn-Ar-metal halide

85 lm/W

33%

80