6. High Pressure Discharge Lamps

Content

6.1 Overview of Low- and High-Pressure Discharge Lamps
6.2 Spectrum of a Hg Discharge
6.3 The High-Pressure Mercury Lamp (HP)
6.4 Phosphors for High-Pressure Mercury Lamps
6.5 The Electrode
6.6 The Electrode Feed Through
6.7 Types of Reflectors
6.8 Application of HP-Lamps
6.9 The High-Pressure Sodium Lamp (HPS)
6.10 Application of HPS Lamps
6.11 Metal-Halide Lamps (MH)
6.12 Photometric Data in Comparison
6.13 Applications of MH Lamps
6.14 UHP-Lamps
6.15 New Developments
### 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><strong>Hg low-pressure (TL)</strong></td>
<td><strong>Hg high-pressure (HPMV = high pressure metal vapour)</strong></td>
</tr>
<tr>
<td><img src="image" alt="Hg low-pressure (TL)" /></td>
<td><img src="image" alt="Hg high-pressure (HPMV)" /></td>
</tr>
<tr>
<td><strong>Hg low-pressure (CFL, PL)</strong></td>
<td><strong>Na high-pressure (HPS = high pressure sod.)</strong></td>
</tr>
<tr>
<td><img src="image" alt="Hg low-pressure (CFL, PL)" /></td>
<td><img src="image" alt="Na high-pressure (HPS)" /></td>
</tr>
<tr>
<td><strong>Na low-pressure (SOX)</strong></td>
<td><strong>Metal-halide high-pressure (MH)</strong></td>
</tr>
<tr>
<td><img src="image" alt="Na low-pressure (SOX)" /></td>
<td><img src="image" alt="Metal-halide high-pressure (MH)" /></td>
</tr>
</tbody>
</table>

**HID = High Intensity Discharge**

---

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 2
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]

Emission spectrum of Hg

200 300 400 500 600

185 254 313 366 408 436 546 577

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 3
6.2 Spectrum of Hg Discharges

Pressure dependence of the lumen output

100 lm/W

20 lm/W

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

Good imaging properties

High luminance

Pressure increase

Pressure

Phosphor

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 4
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**
- **Burner (Hg, noble gas = starting Gas, mostly Xe)**
- **Melting**
- **Electrode**

**Ballast**

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 6
Blue-white light due to the lack of red radiation in the emission spectrum
Solution: Phosphor!

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

Suitable phosphors
(Sr,Mg)₃(PO₄)₂:Sn
Mg₄GeO₅.₅F:Mn
YVO₄:Eu
Y(V,P)O₄:Eu

620 nm  Broadband emission
660 nm  Line emission
620 nm  Line emission
620 nm  Line emission

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

Sn$^{2+}$ or Mn$^{4+}$ phosphors as UV → Red converter

Problem: Low lumen equivalent of these phosphors

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 9
The luminous efficacy under UV-A excitation increases up to about 300 °C
Cause: Increase in spectral overlap with Hg high-pressure discharge spectrum
6.5 The Electrode

Hg low-pressure

- 36 W
- I = 0.36 A
- Tungsten + emitter
- BaO / SrO / CaO
- T = 1350 K

Hg high-pressure

- 400 W
- I = 4 A
- Tungsten + emitter
- BaO / SrO / Y$_2$O$_3$ / ThO$_2$
- T = 2000 - 3000 K
6.6 The Electrode Feedthrough

Problem: Different thermal expansion coefficients

SiO$_2$ $\alpha = 0.5 \times 10^{-6}$ K$^{-1}$
W $\alpha = 4.3 \times 10^{-6}$ K$^{-1}$
Mo $\alpha = 2.8 \times 10^{-6}$ K$^{-1}$
### 6.7 Types of Reflectors

**Parabolic reflectors**

- Focal point (light source)
- Equation: $y = x^2$
- Only possible if the light source is point-like
- HID-lamps

**Elliptical reflectors**

- An ellipse has two focal points
6.8 Application of HP-Lamps

In street lighting (outdoor lighting)

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

The High-Pressure Sodium Lamp (HPS) is characterized by its emission spectrum and lumen output dependence on pressure.

- **Na low-pressure Lamp (0.01 mbar)**
  - Emission peak at 589 nm
  - Lumen output graph showing an increase with increasing pressure up to a peak at 1 bar.

- **Na high-pressure Lamp (100 mbar)**
  - Emission peak at 589 nm
  - Lumen output graph showing a different pattern of output increase compared to the low-pressure lamp.

Pressure dependence of the lumen output is illustrated by the graphs, with the pressure axis ranging from 10 μbar to 1 bar.

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 15
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

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

Polycrystalline structure

Pressure, $1200 \, ^\circ C$

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 16
Widening of the Na-line and self-absorption leads to a spectral hole in the emission spectrum at around 589 nm

\[ p_{\text{Na}} = 150 \text{ mbar (saturated)} \]
\[ p_{\text{Hg}} = 1000 \text{ mbar (buffer gas)} \]
\[ p_{\text{Xe}} = 100 \text{ mbar (start gas)} \]

\[ \eta = 90 - 120 \text{ lm/W} \]
\[ R_a = 20 - 50 \text{ (pressure dependent)} \]
\[ T_c = 1930 \text{ K} \]

\[ n = 1 \]
\[ n = 2 \]
\[ n = 3 \]

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

Architectural and street lighting

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 18
6.11 Metal-Halide High-Pressure Lamps

Filling:
- NaI - TlI - InI
- SnBr₂ - SnI₂
- NaI - DyI₃ (SSTV)
- NaI - ScI₃ (automobile headlight)

Goal: High $\eta$ & color rendering

Incoherent Light Sources
Prof. Dr. T. Jüstel
HPI (High Pressure Iodide) lamps

Fig. 42: The CIE colour triangle, containing the spectrum locus, the system of chromaticity coordinates, the black-body locus and the lines of constant correlated colour temperature for values from 2000 K to 20,000 K.

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

Spectrum of a MH lamp

Hg / NaI / TlI / DyI₃ / Ar
P = 75 W

P_{rad} / P \approx 60 \%
P_{rad,vis} / P \approx 33 \%

Metal-Halide High-Pressure Lamps

Spectral Intensity of CDM (70 W)

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 21
6.11 Metal-Halide High-Pressure Lamps

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
• Metal halides MeXₙ (Me = Na, In, Tl, Sc, Sn, Dy, ...)

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 22
### 6.12 Photometric Data in Comparison

<table>
<thead>
<tr>
<th>Improvement</th>
<th>η (lm/W)</th>
<th>Ra</th>
<th>Color temperature $T_c$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Hg</td>
<td>60</td>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td>+ phosphor</td>
<td>60</td>
<td>50</td>
<td>3800</td>
</tr>
<tr>
<td>High Pressure Na</td>
<td>60 - 130</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>Xe-pressure↑</td>
<td>80 - 150</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>Na-pressure↑</td>
<td>60 - 90</td>
<td>60</td>
<td>2200</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>HPI (NaI-TII-InI) 70 - 80</td>
<td>70</td>
<td>3800 - 4200</td>
</tr>
<tr>
<td>SnBr$_2$-SnI$_2$</td>
<td>70</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>NaI-DyI$_3$</td>
<td>75 - 80</td>
<td>90</td>
<td>3800 - 5600</td>
</tr>
<tr>
<td>NaI-ScI$_3$</td>
<td>80 - 90</td>
<td>75</td>
<td>3600 - 4200</td>
</tr>
</tbody>
</table>

Incoherent Light Sources
Prof. Dr. T. Jüstel
# 6.13 Applications of MH Lamps

<table>
<thead>
<tr>
<th>Material</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPI (NaI-TII-InI)</td>
<td>Street lighting, Architectural lighting, 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, Studio-stage-TV (SSTV), Automotive headlights</td>
</tr>
<tr>
<td>NaI-ScI₃ + Hg + Xe (blue)</td>
<td></td>
</tr>
</tbody>
</table>
6.13 Applications of MH Lamps

SSTV market = Stage-Studio-TV

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 25
6.13 Applications of MH Lamps

In the „beamer“

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

- Rückwärts-Projektion

- Professionelle Präsentationen

Warum Projektion?
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)

Lamp at the focal point in a parabolic reflector
Collecting lens
Slide
Projection screen
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
Components of UHP-Lamps

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

Description of UHP-lamp by
- 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
  \[ \frac{\partial^2 h}{\partial x'^2} + \frac{\partial^2 h}{\partial y'^2} = 0 \]
  Potential: \( h = z + \frac{u}{\gamma w} \)

- Energy balance of the electrodes and the wall
6.14 UHP-Lamps

Temperaturbelastung des Quarzglases
Elektrodentemperatur und Belastung der Einschmelzung

Incoherent Light Sources
Prof. Dr. T. Jüstel

Chapter High Pressure Discharge Lamps
Slide 32
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

Light source with extremely high light output, about 140000 lm (~ 40 fluorescent tubes) and (almost) pure-white light (emission band of \( S_8 \), \( S_6 \), ..., \( S_2 \) molecules)

**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

**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. $S_2$

6.15 New Developments

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

Zn/Ar Discharge

\[ \text{W}_{\text{el}} = 75 \text{ W} \]
\[ \text{LE} = 114 \text{ lm/W} \]
\[ x = 0.228, \ y = 0.227 \]
\[ T_c = 34000 \text{ K} \]
\[ \text{Efficacy} = 20 \text{ lm/W} \]
\[ \varepsilon = 0.174 \frac{\text{W}_{\text{opt}}}{\text{W}_{\text{elektr}}} \]
\[ R_a = 0 \]

Zn/Ar/metal halide Discharge

\[ \text{W}_{\text{el}} = 75 \text{ W} \]
\[ \text{LE} = 280 \text{ lm/W} \]
\[ x = 0.436, \ y = 0.387 \]
\[ T_c = 3000 \text{ K} \]
\[ \text{Efficacy} = 85 \text{ lm/W} \]
\[ \varepsilon = 0.33 \frac{\text{W}_{\text{opt}}}{\text{W}_{\text{elektr}}} \]
\[ R_a = 80 \]

<table>
<thead>
<tr>
<th></th>
<th>Zn-Ar</th>
<th>Zn-Ar-metal halide</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>20 lm/W</td>
<td>85 lm/W</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>17%</td>
<td>33%</td>
</tr>
<tr>
<td>( R_a )</td>
<td>0</td>
<td>80</td>
</tr>
</tbody>
</table>