4. Incandescent and Halogen Lamps

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4.1 History

- **1820**: Arthur de la Rive observes a glowing Pt-wire in vacuum
- **1840**: Joseph Wilson Swan experiments with carbonised paper wires
- **1854**: Heinrich Goebel constructs the first incandescent lamp with a bamboo fiber, which finally leads to the carbon filament lamp
  
  Problem: still not sufficiently well evacuated \( \Rightarrow C + O_2 \rightarrow CO_2 \)

- **1868**: First fabrication of incandescent lamps by Swan (low lifetime)
- **1879**: Patent of Thomas Alva Edison
  
  Edison improves incandescent lamps by better evacuation of the lamp bulb \( \rightarrow \) higher lifetime

- **1881**: Demonstration (Presentation) of Edison Lamp at the World Exhibition in Paris
  
  Searching for high melting metals \( \rightarrow \) Ta, W, Re, Os
  
  Winner: Tungsten because of the lowest vapour pressure \( \Rightarrow \) lowest blackening

- **1900**: Max Planck: Theoretical basis (Planck's law)
- **1902**: Osmium wire (Auer and Welsbach)
- **1911**: Ar/N₂ filling
- **1912**: Tungsten wire
- **1936**: First lamp with a double coiled filament
- **1958**: First application of Xenon as a filling gas
- **1960**: Halogen cycle (Zubler and Mosby, GE)
- **1971**: First H4 automotive lamp (today also H7)
- **1973**: First halogen lamp with interference filter
- **2010**: Incandescent lamps marketed as heat balls
4.2 Physical Fundamentals

Energy balance of an incandescent lamp

- Input Power
- Electromagnetic radiation
- Gas losses
- Conductivity losses
- IR
- Visible
- UV

Tungsten filament with the electrical resistance $R$

Electric loss for current $I$

$P = U \cdot I = R \cdot I^2$

Spectrum of a glowing filament at about $T = 2700$ K (incandescence)
4.2 Physical Fundamentals

The black body radiation can be defined as the light emission in thermal equilibrium (thermal radiation)

Planck's radiation law (1900)

\[ L_e = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^{c_2/\lambda T} - 1} \]

- \( c_1 = 2\pi hc^2 = 3.741832 \cdot 10^{-16} \text{ Wm}^2 \)
- \( c_2 = hc/k = 1.438786 \cdot 10^{-2} \text{ Km} \)
- \( \lambda = \text{Wavelength [m]} \)
- \( L_e = \text{Spectral irradiance (radiation density)} \)
- \( T = \text{Temperature [K]} \)

**Spectrum of a black body radiator**

**Wien's displacement law**

\[ \lambda_{\text{max}} \cdot T = 2880 \text{ [µm} \cdot \text{K]} \]

**Light source** | **Color temperature**
--- | ---
Sun | 5800 K
Studio halogen lamp | 3400 K
Halogen lamp | 3000 K
Incandescent lamp (bulb) | 2700 K
4.2 Physical Fundamentals

Incandescent and halogen lamps are spatially and temporally incoherent light sources

Incoherence

Temporally coherence

Spatially and temporally coherence

A light bulb radiates incoherent: the wavelengths of the individual waves are different or between the various points of the radiating surface, there is no fixed phase relationship.

A color filter allows only light of a certain wavelength to pass through: the radiation is temporally coherent (monochromatic).

Through color filter and pinhole a small-area, temporally and spatially coherent light source of very low intensity is created.
4.3 Construction

Fill gas = noble gas (Ar, Kr, Xe) + N₂ (pressure = 1 bar)
Typical: 80% N₂ + 20% Ar

Ar 39.9 g/mol
Kr 83.8 g/mol
Xe 131.3 g/mol

Screw thread = Edison-Type
Bajonett-Type
Diameter in mm
Europe  E10  E14  E27  E40
USA    E12  E17  E26  E39

Filament is double coiled

It is coiled initially on Mo, then Mo is removed
4.3 Construction

From a glass bulb to an incandescent lamp
4.3 Construction

**Production of tungsten filament**

**Tungsten production**

Ores: CaWO₄ or (Fe,Mn)WO₄
- “Scheelite” “Wolframite”
- Digestion with HCl
- MeCl₂ + WO₃·H₂O “Tungstite”
- Leaching with NH₃
- (NH₄)₁₀[H₂W₁₂O₄₂] “Paratungstate”
- 600 °C
- WO₃
- Doping, H₂, 450 °C
- α-W-metal powder → Pressing + sintering to W-staves

**Filament production**

W-staves
- Hammering, rolling
W-plates
- Pulling
W-wires
- Winding/coiling
W-filament

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4.4 Lifetime

Blackening of incandescent lamps

Tungsten which evaporates from the filament condenses inside of the glass bulb.

Tungsten has the lowest vapour pressure of all metals and the highest melting point of all metals (Tm = 3410 °C), Carbon (graphite) melts at 3550 °C.
4.4 Lifetime

The hotter is the filament, the more efficient is an incandescent lamp, however blackening is then also stronger.

Operating conditions of an incandescent lamp represent a compromise between the energy efficiency $\eta$ and lifetime $t$.

Typical values for operation at nominal voltage: $\eta = 13 \text{ lm/W}$ and $t = 1000 \text{ h}$.

“Hot spot“- mechanism
W-wire becomes thinner
$\Rightarrow$ Resistance increases
$\Rightarrow$ Local output and temperature increase
$\Rightarrow$ Vapour pressure increases
$\Rightarrow$ Burning-out at “hot spot“
4.5 Halogen Incandescent Lamp

Functional principle

In halogen incandescent lamp tungsten is transported back to the filament from glass bulb via chemical transport ⇒ Glass bulb remains clear

Filling gas = nobel gas + O₂ + X₂ (X = Br, I)

= Solubility curve
  = pₖ+W + pₖ+WO + pₖ+WBr + .....
4.5 Halogen Incandescent Lamp

Chemical transport in halogen incandescent lamps

The position of the chemical equilibrium is temperature dependent: \( W + O_2 + X_2 \rightleftharpoons WO_2X_2 \)

\[
\ln K = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}
\]

van't Hoff

Halogen-cycle

- \( W \) = Tungsten Filament
- \( X \) = Halogen X
- \( W + nX \) = Halogen X
- \( W+nx \) = Halogen X

T = Filament

\( \ln K_1 < 0 \)

\( \ln K = 0 \)

\( \ln K_2 > 0 \)

\( T_1 = \) Filament

\( \rightarrow W(s) + O_2(g) + X_2(g) \)

\( T_2 = \) Wall

\( \rightarrow WO_2X_2(g) \)
4.5 Halogen Incandescent Lamp

Limitation of the W-Recycling

- Although W back transport is efficient, no curing of the W-filament occurs
- Gaseous W condenses at the cold spot (thickest section due to lowest resistance)

\[
\begin{align*}
W + \frac{1}{2} O_2 & \rightleftharpoons WO \\
WO + \frac{1}{2} O_2 & \rightleftharpoons WO_2 \\
WO_2 + \frac{1}{2} O_2 & \rightleftharpoons WO_3
\end{align*}
\]

\[
2W(s) + 3O_2(g) \rightleftharpoons 2WO_3(s) \quad \Delta H = -764 \text{ kJ/mol}
\]
4.5 Halogen Incandescent Lamp

Set of problems with UV-radiation

Due to the higher filament’s temperature, halogen incandescent lamps emit also some of UV-A and UV-B radiation, since the quartz bulb is transparent to UV radiation.

Transmission spectrum of quartz glass

Transmission and emission spectrum of Ce$^{3+}$ doped silica glass
4.5 Halogen Incandescent Lamp

Advantages over incandescent lamps

In halogen incandescent lamp remains the (bulb) wall, during the chemical transport, clear
⇒ Reduction of bulb size
⇒ Increase the noble gas pressure
⇒ Lower evaporation rate of tungsten gives a higher lifetime, what gives partly higher efficiency (higher filament temperature)

<table>
<thead>
<tr>
<th>T [K]</th>
<th>( \eta ) [lm/W]</th>
<th>( \eta ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>2800</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>3000</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>3200</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>3400</td>
<td>36</td>
<td>20</td>
</tr>
</tbody>
</table>
4.6 Interference Filter

Since incandescent lamps and halogen incandescent lamps emit substantially IR-radiation, even higher efficiencies can be achieved by IR filter.

Principle on the example of the halogen lamp

Visible light is transmitted

IR light is reflected back to the filament

\[ \eta = 20 \text{ lm/W} \Rightarrow 40 \text{ lm/W} \]

Interference filter
4.6 Interference Filter

Interference filters consist of a sequence of low- and highly refractive inorganic layers.

Path difference = \(2d - \lambda/2\)

Glass (\(n = 1.5\))

\(\text{TiO}_2, \text{ZnS, ... (}n = 2.3 - 2.7\))

Example: \(2nd = 500\) nm

- Low reflectance:
  - \(k=0\): \(\lambda = 500\) nm
  - \(k=1\): \(\lambda = 500/2 = 250\) nm
  - \(k=2\): \(\lambda = 500/3 = 167\) nm
  - ......

- High reflectance:
  - \(m=0\): \(\lambda = 500/0.5 = 1000\) nm
  - \(m=1\): \(\lambda = 500/1.5 = 333\) nm
  - \(m=2\): \(\lambda = 500/2.5 = 200\) nm
  - ......

\(m\lambda\) Constructive interference

High reflectance

\((k+1/2)\lambda\) Destructive interference

Low reflectance

Visible

IR

200 400 600 800 1000 \(\lambda [\text{nm}]\)

1 Layer

Up to 40 layers
4.6 Interference Filter

Energy saving filter

Cold light mirror is an inverse energy saving filter:
It reflects visible light and let IR radiation pass through.

Cold light reflector are not perfect, i.e. deep red and deep blue are visible behind the lamp
4.6 Interference Filter

Interference filter as colour filter

Application in light sources and spectrometers

Lack of blue in emission spectrum $\Rightarrow$ yellow filter
4.7 Types of Halogen Lamps

**Halogen lamps for general lighting**

- **Power (P)**: 200 - 500 W
- **Voltage (U)**: 230 V

Using the formula:

\[ P = U^2 / R \]

This implies:

- \( U \) increases \( \Rightarrow R \) increases
- \( R = \rho * l / A \)
- Longer and thinner filament
- Filament is less stable
- **\( T_{filament} \) is lowered**
- **\( \eta \) decreases in comparison with low voltage lamps**

**Low-voltage halogen lamps**

- **Voltage**: 12, 24 V (Transformer is required)
- **Power (P)**: 20 - 50 W

- **Outer envelope** (hot & fingerprints)
- **PAR** = Parabolic reflector lamp

**High-voltage halogen lamps**
### 4.7 Types of Halogen Lamps

#### Low Voltage vs. High Voltage Halogen Lamps

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>Low voltage</th>
<th>High voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage U [V]</td>
<td>12</td>
<td>230</td>
</tr>
<tr>
<td>Power P [W]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Filament length l [cm]</td>
<td>2.21</td>
<td>15.81</td>
</tr>
<tr>
<td>Diameter d [μm]</td>
<td>54.1</td>
<td>7558</td>
</tr>
</tbody>
</table>

\[
1 = \sqrt[3]{\frac{P}{4 \pi \rho \sigma^2 T^8}}
\]

\[
d = \sqrt[3]{\frac{P^2 \rho}{\sigma \pi^2 T^4 U^2}}
\]
4.7 Types of Halogen Lamps

- **Car head lights**
  - Drive light (high beam)
  - Dimmed head lights (low beam)

- **H7-Lamps (1 Filament)**
- **H4-Lamps (2 Filaments)**

- **Drive light (high beam)**
- **Dimmed head lights (low beam)**

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4.7 Types of Halogen Lamps

Halogen lamps SSTV Market (Stage-Studio-TV)

Headlamp

Fresnel lens

Original filament
Picture of a filament

Spherical mirror

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4.8 New Developments

White LEDs are becoming strong competition for halogen incandescent lamp

<table>
<thead>
<tr>
<th>Light source</th>
<th>Luminous flux</th>
<th>Efficiency [lm/W]</th>
<th>Brightness [Mcd/m²]</th>
<th>CRI</th>
<th>Lifetime [kh]</th>
<th>Costs [$/Mlm·h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent</td>
<td>60 W</td>
<td>900</td>
<td>15</td>
<td>10</td>
<td>100</td>
<td>7.2</td>
</tr>
<tr>
<td>Halogen</td>
<td>50 W</td>
<td>1000</td>
<td>20</td>
<td>20</td>
<td>100</td>
<td>6.3</td>
</tr>
<tr>
<td>LED 2002</td>
<td>125</td>
<td>250</td>
<td>25</td>
<td>3</td>
<td>75</td>
<td>6.0</td>
</tr>
<tr>
<td>LED 2013</td>
<td>1000</td>
<td>250</td>
<td>10</td>
<td>90</td>
<td>60</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

Further development of incandescent and halogen bulbs

Tungsten filament with photonic band structure via 3D-structuring.
Aim: Reduction of the IR-emission and therefore increasing the light efficiency.
4.8 New Developments

Specialties

High performance lamps (up to 20 kW)  Colored incandescent lamp (coated with inorganic metal oxides)

- High performance lamps
- Colored incandescent lamp with CoAl$_2$O$_4$
- Colored incandescent lamp with Fe$_2$O$_3$
4.8 New Developments

**Specialties**

Doping of the lamp glass, e.g. by Nd$_2$O$_3$ (GE Lighting: Reveal®)

**Aim:**
- Increase of the color temperature without loss of color rendering
- Enhancement of the contrast between red and green

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Specialties

2010: Marketing of incandescent lamps as heatballs, as a reaction on the ban of incandescent lamps driven by the EU

2016: Ban of halogen lamps implemented