1. BASIC DEFINITIONS
   - Thermal radiation
   - Thermo-radiative properties
   - Optical Pyrometry

2. SOLAR BLIND MEASUREMENTS
   - Principles
   - Studies Exemples

3. TEMPERATURE MEASUREMENTS
   - Apparatus and methods
   - Two colour Pyroreflectometry
   - Studies Exemples
Temperature is a subjective concept based on cold and hot sensation.

Temperature is an intensive value.

Temperature is a subjective concept based on cold and hot sensation.

Temperature is measured through a temperature scale: IST 90.
## ITS & THERMODYNAMIC TEMPERATURE

### ITS 90

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Elem.</th>
<th>State</th>
<th>Inst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 à 5</td>
<td>He</td>
<td>V</td>
<td>1 et 2</td>
</tr>
<tr>
<td>13.8033</td>
<td>e-H₂</td>
<td>T</td>
<td>2 et 3</td>
</tr>
<tr>
<td>17</td>
<td>e-H₂</td>
<td>V</td>
<td>2 et 3</td>
</tr>
<tr>
<td>20.3</td>
<td>e-H₂</td>
<td>V</td>
<td>2 et 3</td>
</tr>
<tr>
<td>24.5561</td>
<td>Ne</td>
<td>T</td>
<td>2 et 3</td>
</tr>
<tr>
<td>54.3584</td>
<td>O₂</td>
<td>T</td>
<td>3</td>
</tr>
<tr>
<td>83.8058</td>
<td>Ar</td>
<td>T</td>
<td>3</td>
</tr>
<tr>
<td>234.3156</td>
<td>Hg</td>
<td>T</td>
<td>3</td>
</tr>
<tr>
<td>273.16</td>
<td>H₂O</td>
<td>T</td>
<td>3</td>
</tr>
<tr>
<td>302.9146</td>
<td>Ga</td>
<td>F</td>
<td>3</td>
</tr>
<tr>
<td>429.7485</td>
<td>In</td>
<td>C</td>
<td>3</td>
</tr>
<tr>
<td>505.078</td>
<td>Sn</td>
<td>C</td>
<td>3</td>
</tr>
<tr>
<td>692.677</td>
<td>Zn</td>
<td>C</td>
<td>3</td>
</tr>
<tr>
<td>933.473</td>
<td>Al</td>
<td>C</td>
<td>3</td>
</tr>
<tr>
<td>1234.93</td>
<td>Ag</td>
<td>C</td>
<td>3 et 4</td>
</tr>
<tr>
<td>1337.33</td>
<td>Au</td>
<td>C</td>
<td>4</td>
</tr>
<tr>
<td>1357.77</td>
<td>Cu</td>
<td>C</td>
<td>4</td>
</tr>
</tbody>
</table>

°C = K –273.15 K

- **V**: Pt. of vapor pression
- **F**: Fusion
- **T**: Pt. triple
- **C**: Freezing
- **1**: Ther. He vapor pression
- **2**: Ther. He gas pression
- **3**: Ther. Pt resistance
- **4**: Optical pyrometry

---

### Carnot Cycle on a Perfect Gas

\[ \frac{Q_2}{Q_1} = \frac{f(T_2)}{f(T_1)} \]

\[ f(T) = aT \]

### Theory of Gas Kinetic

Temperature is linked to molecule or particle movements

---

Sir W. Thomson → Lord Kelvin 1852

**FIRST DEFINITION OF MEASURABLE T**
**THERMAL RADIATION is ENERGY**

Temperature is linked to thermal radiation

- **Cosmics Rays**
  - γ rays
  - X rays
  - UV
  - Visible
  - Infrared
  - Radio waves

<table>
<thead>
<tr>
<th>λ (µm)</th>
<th>UV</th>
<th>VISIBLE</th>
<th>NIR</th>
<th>MIR</th>
<th>LIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.4</td>
<td>0.75</td>
<td>1.5</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>

**ELECTROMAGNETIC SPECTRUM**

Max Planck 1858-1947

Quantum mechanics

- Emission
- Fundamental
- Quantum \( h \nu \)
- Absorption

\[
I^0(T, \lambda) = \left( \frac{C}{\pi} \right) \left[ \lambda^3 \left( \exp \frac{C_2}{\lambda^4} - 1 \right) \right]
\]

- \( C_1 = 2hc^2 \) = \( 3.7415 \times 10^{-16} \) W.m² sr⁻¹
- \( C_2 = \frac{hc}{k} \) = \( 1.4388 \times 10^{-2} \) mK

\( c \) : Light celerity in vacuum
\( h \) : Planck constant
\( k \) : Boltzmann constant
The Blackbody is the reference source for Thermal Radiation

Definition: Total absorption of thermal radiation
Property: Emission follows Planck Law and it is isotropic

Isothermal Planck curves
90% of energy emitted between

\[ 0.5 \lambda_m < \lambda < 5 \lambda_m \]

Isochromatic Planck curves

\[ \lambda_{\text{max}} = 2897 \mu \text{mK} \]
THERMAL RADIATION AND REAL BODY

**Emission**

\[ I^j = \varepsilon^j I^o \]

**Interaction Material-Thermal Radiation**

**Energy Conservation**

\[ \alpha + \rho + \tau = 1 \]
EMISSION of REAL BODY

\[ I^\circ(\lambda,T): \text{Wm}^{-3}\text{Sr}^{-1} \]

- **Real Body at 2000°C**
- **Black Body at 2000°C**
- **Grey Body \( \varepsilon = 0.75 \) at 2000°C

EMISSION AND PROPERTIES
- DIRECTIONAL DEPENDENT

**PARTICULAR PROPERTIES**
- \( \varepsilon(\lambda,T) \) isotropic
- \( \varepsilon(T) \) grey body

\[ E^j(T,\lambda) = \frac{I^j(T,\lambda)}{I^o(T,\lambda)} \]

Emissivity \( \leq 1 \)
**Radiative Properties**

Absorptivity
\[ \alpha^i(T,\lambda) = \frac{d^2 \Phi_{a,i}}{d^2 \Phi_{i,i}} \]

Reflectivity
\[ \rho^{\|}(T,\lambda) = \frac{d^2 \Phi_{r,i}}{d^2 \Phi_{i,i}} \]

Transmitivity
\[ \tau^i(T,\lambda) = \frac{d^2 \Phi_{t,i}}{d^2 \Phi_{i,i}} \]

**Particularity of the reflection:**

directional hemispherical

**Bidirectional reflectivity or B.R.D.F.**

\[ \rho^{ij}(T,\lambda) = \frac{\int \Phi^{ij}(\lambda) \cos(\Theta_i) d\Omega_i}{\int \Phi^{ij}(\lambda) \cos(\Theta_j) d\Omega_j} \]

\[ \rho^{ij}(T,\lambda) = \int_{\Omega} \rho^{ij}_{\text{F.D.}}(T,\lambda) \cos(\Theta_j) d\Omega_j \]

\[ \rho^{\|}(T,\lambda) = \pi \rho^{ij}_{\text{F.D.}}(T,\lambda) \]

\[ \rho^{ij}_{\text{F.D.}}(T,\lambda) \rightarrow +\infty \]

**Isotropic Reflexion**

**Specular Reflexion**
RADIATIVE PROPERTIES RELATIONS

1st Kirchoff Law

\[ \alpha^j(T,\lambda) + \rho^{j,\cap}(T,\lambda) + \tau^j(T,\lambda) = 1 \]

2nd Kirchoff or Draper law

\[ \alpha^j(T,\lambda) = \varepsilon^j(T,\lambda) \]

Helmholtz reciprocity

\[ \rho_{F.D.}^{i,j}(T,\lambda) = \rho_{F.D.}^{j,i}(T,\lambda) \]

\[ \alpha^j(T,\lambda) = 1 - \rho^{j,\cap}(T,\lambda) \]

\[ \rho^{i,\cap}(T,\lambda) = \rho^{\text{iso}}^{\cap}(T,\lambda) \]
**PYROMETRY PRINCIPLE**

**Measure on a Real Body**

\[
S^j(T,\lambda) = k I^j(T,\lambda) = k I^0(T_{R,\lambda}) = k \varepsilon^j(T,\lambda) I^0(T,\lambda)
\]

Wien Approximation

\[
L^0(T,\lambda) = \left(\frac{C_1}{\pi}\right) \left[\lambda^2 \exp\left(\frac{C_1}{\lambda}\right)\right]
\]

\[\lambda T < 14400 \mu mK\]

\[
\frac{1}{T} = \frac{1}{T_{R,\lambda}} + \frac{\lambda}{C_2} \ln(\varepsilon^j(T,\lambda))
\]
PYROMETER ARCHITECTURE

**Optical Components**
- Miror
- Filter
- Diaphragm
- Lens
- Split
- Δλ

**Detection**
- Modulator
- Reference
- Split
- O.F.

**Emission**
- Pbs
- PbSe
- InSb 200K
- InAs
- InGaAs-Ge
- PbS
- Laser 77K

**Detectivity**

\[
S(T, \lambda) = kI^O(T, \lambda)
\]

\[
S^j(T, \lambda) = kI^j(T, \lambda) = kI^O(T_{R, \lambda}) = k\varepsilon^j(T, \lambda)I^O(T, \lambda)
\]

\[
T \geq T_{R, \lambda}
\]
LAB APPARATUS - RADIANCE TEMP.

- Blackbodies
- Spectro-radiometer
- Pyrometer
REALITY OF THE MEASURE

\[
S^j(\lambda, T) = a(\tau_{o,t}^j(\lambda)) \left[ \mathcal{E}^j(\lambda, T)I^0(\lambda, T) + \iint \rho_{F,D}^i,j(\lambda, T)I^i \cos(\theta_i) d\cap_i + \iint \tau^i(\lambda, T)I^i d\cap_i \right]
\]
ANALYSIS AND EXPERIMENTAL RESULTS OF SOLAR-BLIND TEMPERATURE MEASUREMENTS IN SOLAR FURNACES
JSE 2004 Vol 126/645-653
Blackbody condition
\[ \rho = 0 \]

Chromatic occultation
\[ \tau_a(\lambda) = 0 \quad \text{or} \quad \tau_w(\lambda) = 0 \]

Temporary occultation
\[ I_s(\lambda) = 0 \]
\[ \eta(\lambda) = \tau_a(\lambda) R^2(\lambda) \]
SPECTRAL SOLAR BLIND ERRORS

Error °C

1.6µm 4
1.4µm with Δλ=45nm 2
1.38 & 1.4µm with Δλ=10nm 3
1.86µm 5
3.9µm 7
8-12µm 10

0 500 1000 1500 2000 2500 3000
T °C

1.86µm
8-12µm
1.4µm with Δλ=45nm
1.38 & 1.4µm with Δλ=10nm
REALITY OF THE MEASURE

\[ S^j(\lambda,T) = a(\tau_{o,i}^j(\lambda)) \left[ \varepsilon^j(\lambda,T)I^0(\lambda,T) + \int \int \rho_{F,D}^i(\lambda,T)I^i \cos(\theta_i)d\cap_i + \int \tau^i(\lambda,T)I^i d\cap_i \right] \]
# APPARATUS AND METHODS

<table>
<thead>
<tr>
<th>Monochromatic Pyrometer</th>
<th>Bi Chromatic Pyrometer</th>
<th>Spectro Radiometer</th>
<th>Infrared Camera</th>
</tr>
</thead>
</table>

1. **MONOCHROMATIC PYROMETRY**
2. **BICOLOR PYROMETRY**
3. **UV PYROMETRY**
4. **MULTI-COLOR PYROMETRY**
5. **ACTIVE PYROMETRY**
6. **CHRISTIANSEN POINT PYROMETRY**
7. **PYRO LASER**
8. **BICOLOR PYROREFLECTOMETRY**

---

### Equations

1. **Emissivity assumption**
   \[ L^j(T,\lambda) = L^0(T_{L,\lambda}) = \varepsilon^j(T,\lambda) L^0(T,\lambda) \]

2. **Grey Body assumption**
   \[ \frac{L^j(T,\lambda)}{L^0(T,\lambda)} = \frac{L^0(T_{C,\lambda},\lambda)}{L^0(T_{C,\lambda},\lambda)} = \frac{\varepsilon^j(T,\lambda)}{\varepsilon^j(T,\lambda)} L^0(T,\lambda) \]

3. **Measurements at 0.3µm: photomultipliers**
   \[ \frac{1}{T} = \frac{1}{T_{R,\lambda}} + \frac{\lambda}{C_2} \ln(\varepsilon^j(T,\lambda)) \]

4. **Measurements at several wavelengths**
   \[ \varepsilon^j_{\lambda} = \exp(a_0 + a_1 \lambda) \]

5. **Determination of \( \alpha^j(T,\lambda) \) through \( T \) incrementation with controlled laser flux**
The method need a preliminary lab. studies

Limited to pure dielectrics materials

Choice of a pyrometer with adapted wavelength
PYROREFLECTOMETRY

FIRST WORKS: OPTICAL DETECTION

Traverse, Foex, Badie: 1976

\[ L \tilde{J}_o(T,\lambda) = L^O(T_{R,\lambda}) = \varepsilon \tilde{J}_o(T,\lambda) L^O(T,\lambda) = (1 - \rho \tilde{J}_o \cap (T,\lambda)) L^O(T,\lambda) \]

\[ \rho \tilde{J}_o \cap (T,\lambda) = [\left( D^{E+R}(T,\lambda) - D^E(T,\lambda) \right) / D^R_o(T_o,\lambda)] \rho_o \tilde{J}_o \cap (T,\lambda) \]

1. MEASURE ON REFLECTIVE REFERENCE
2. MEASURE OF EMISSION
3. MEASURE OF EMISSION + REFLECTION

COMMERCIAL VERSION
'Pyrolaser'

LIMITED TO LAMBERTIAN SURFACE
FUNDAMENTAL ASSUMPTION

Same indicatrix of reflected fluxes for two near wavelengths \( \lambda_r \) and \( \lambda_b \) with:

\[
\rho_{F.D.}^{i,j}(T,\lambda_r) \neq \rho_{F.D.}^{i,j}(T,\lambda_b)
\]

Condition no so restrictive as grey or diffuse one
Two Colour Pyroreflectometry

\[ L_\beta^j(T,\lambda) = L_\beta^O(T_{R,\lambda}) = e_\beta \tilde L_\beta^O(T,\lambda) = (1 - \rho_\beta^j (T,\lambda)) L_\beta^O(T,\lambda) \]

\[ \rho_\beta^j (T,\lambda) = \int \rho_F^j (T,\lambda) \cos(\theta_i) d\Omega_i = \int \rho_F^j (T,\lambda) \int \rho_F^j (T,\lambda) \cos(\theta_i) d\Omega_i \]

**Introduction of the Diffusion Factor**

\[ \eta_d^j (T,\lambda) = \int \rho_F^j \cos(\theta_i) d\Omega_i / \int \cos(\theta_i) d\Omega_i = \left( \rho^j (T,\lambda) / \rho_F^j (T,\lambda) \right) / \pi \]

\[ L_\beta^O(T_{R,\lambda}) = (1 - \pi \eta_d^j (T,\lambda) \rho_F^j (T,\lambda)) L_\beta^O(T,\lambda) \]

\[ L_\beta^O(T_{R,\lambda_r}) = (1 - \pi \eta_d^j (T,\lambda) \rho_F^j (T,\lambda)) L_\beta^O(T,\lambda_r) \]

\[ L_\beta^O(T_{R,\lambda_b}) = (1 - \pi \eta_d^j (T,\lambda) \rho_F^j (T,\lambda)) L_\beta^O(T,\lambda_b) \]

Solvable System measuring:

- \( T_{R,\lambda_r} \)
- \( T_{R,\lambda_b} \)
- \( \rho_F^j (T,\lambda_r) \)
- \( \rho_F^j (T,\lambda_b) \)
THREE DIFFERENT CASES

Simulation for $T=1000 \, ^\circ C$ and $\eta = 1/\pi$

- $\rho_r = \rho_b \Rightarrow T_C = T$
  - Bicolor Pyrometry

- $\rho_r > \rho_b \Rightarrow T_C > T$
  - Bicolor - Pyroreflectometry

- $\rho_r < \rho_b \Rightarrow T_C < T$
  - Tricolor - Pyroreflectometry
**EXPERIMENTAL VALIDATION**

1. Graph showing temperature vs. emissivity for different materials and wavelengths.
2. Graph showing temperature vs. emissivity for Inconel material.
3. Graph showing temperature vs. angular distribution.

\[ \eta_d(800°C) = 0.201 \]  
\[ \eta_d(800°C) = 0.202 \]
Diodes Characteristics
\( \lambda_r := 1.55 \mu m - \lambda_b := 1.30 \mu m \)
Frequency: 10kHz (1µs & 99µs)
Output power: 60mW

Optical Fiber Characteristics
Silica, Step index, N.A. = 0.22,
Core diam. 100, 200, 400, 500µm

Measurement Principle
\[
M1 \Rightarrow f(\rho^{i,j}(\lambda)) \\
M2 \Rightarrow f(L(\lambda, T_R)) \\
(M3 - M2) / M1 \Rightarrow f(\rho^{i,j}(\lambda, T_R))
\]

Measured parameters
\[
\text{Tr}(\lambda_r), \text{Tr}(\lambda_b), \text{Tc}(\lambda_r, \lambda_b) \\
\rho^{i,j}(\lambda_r), \rho^{i,j}(\lambda_b)
\]

\( T_{\text{min}} : 600°C \)
\( \Delta T : +/- 5° \)
\( \Delta \rho/\rho : 2% \)
THE PROBES

PROXIMITY

PROBE WITHOUT LENSES

REMOTE

Typical size: 3-5mm diameter

\[ r_s = \tan(\theta_{out})d \]

\[ \frac{1}{p} + \frac{1}{p'} = \frac{1}{f} \]

\[ G = \frac{R_i p'}{R_f p} \]

TWINS LENSES PROBE

POLKA DOT PROBE

Typical size: 3-5mm diameter
THE DIFFUSION FACTOR

\[ \eta_d \rightarrow 1 \]

\[ \eta_d \rightarrow 0 \]

\[ \eta_d \]
Surface Classification with $\varepsilon$ and $\eta$

Pyroreflectometry to determine the true temperature and optical properties of surfaces J.S.E.Volume: 130 Issue: 3 Published: 2008
PYROREFLECTOMETRY AT PROMES

1 MW INSTALLATION
 'GRAND FOUR'
 MEDIASE

2 kW INSTALLATION
 'BASTION'
 DISCO
MEASUREMENTS ON TUNGSTEN

Validation

Characterisation

\[ T(T^*) = 1149 \]

\[ T(T^*) = 1162 \]

\[ T_c (1.3 \text{ & } 1.55 \text{ μm}) \]

\[ T(T^*) = 1162 \]

\[ T(T^*) = 1162 \]

\[ T_b = 1059 \]

\[ T(T^*) = 1032, T_b = 1059 \]

\[ \eta_d = 0.123 \]

\[ \rho_{a} = 1.085, \rho_{b} = 1.0 \]

\[ T_c (1.3 \text{ & } 1.55 \text{ μm}) \]

\[ T_r (1.55 \text{ μm}) \]

\[ T_b (1.3 \text{ μm}) \]

\[ \epsilon(\theta) \]

\[ \eta, \rho_r/\rho_b \]

W clean (Sample n°2)
MEASUREMENTS ON COPPER

Mesures déportées

Mesures: \( T_c = 1185 \) - \( T_r = 759 \) - \( T_b = 803 \) - \( \rho_r = 0.49 \) - \( \rho_b = 0.445 \)

\( T \) = 945°C

\( \eta_d \) = 0.431

\( T_{th} \) = 955°C

\( T_{r,1.3\mu m} \) - \( T_{b,1.3\mu m} \) - \( T_{r,1.55\mu m} \) - \( T_{b,1.55\mu m} \)
Aluminium Specular Temperatures - Phase 1

Aluminium Specular Optical Properties - Phase 1
THERMOREFLECTOMETRY

Sample with 4 areas

Pixel levels

Color temperature

Graphs showing temperature variation with diffusion factor for Silver, Copper, White, and Black samples.
ADVANTAGES OF PYROREFLECTOMETRY

- The less restrictive assumption
- In situ and on line measurements
- Permanent control of all the parameters
- Large experimental validation
- Large industrial application in rough conditions
- Surface control for non contact diagnostic
- Mature technique
- Possibility to be extended forward solar blind wavelengths
- Possibility to be extended for spatial measurements 'IR Camera'

A concept to determine the true temperature of opaque materials using a tricolor pyroreflectometer
REVIEW OF SCIENTIFIC INSTRUMENTS Volume: 76 Issue: 2 Published: 2005

Development of two-colour pyroreflectometry technique for temperature monitoring of tungsten plasma facing components FUSION ENGINEERING AND DESIGN Volume: 83 Pages: 672-679 Published: 2008

True temperature measurement on metallic surfaces using a two-color pyroreflectometer method
REVIEW OF SCIENTIFIC INSTRUMENTS Volume: 80 Issue: 9 Published: 2009

Experimental validation of a pyroreflectometric method to determine the true temperature on opaque surface without hampering reflections MEASUREMENT Volume: 42 Issue: 6 Pages: 836-843 Published: 2009
Temperature determined with two colour pyroelectrometric method

Thermocouple

Pyroreflectometer

Infrared Camera

Temperature determined with two colour pyroelectrometric method

FE200 (CEA-AREVA)
APPLICATION ON FUSION REACTOR (ITER)

80 m of optical fiber linking Calibration

ASDEX-UPGRADE Max Planck Institute (Garching)
APPLICATION ON FUSION REACTOR (ITER)
APPLICATION ON FUSION REACTOR (ITER)
Oxidization of ZrO\(_{2-x}\)

Hermes winging edge true temperature (Plata forma solar Almeria)
Measurement inside 3mm cooling canal

Inconel

T°C
1000
950
900
850
800
750
700
650
600
550
0,0
0,5
1,0
1,5
2,0
2,5
3,0

Tc=770 Tr=737 Tb=742 Tv=753
ρr=0.265  ρb=0.239  ρv=0.220
η = 0.65

Réflectivités normales normales

0,00 0,05 0,10 0,15 0,20 0,25 0,30 0,35
0 25 50 75 100 125 150 t en s

Réflectivité à 1,55µm
Réflectivité à 1,3µm

Temperatures en °C

Tc
Tvc
TIR
TvLR
Tb
TvLB

Inconel

T°C
1000
950
900
850
800
750
700
650
600
550
0,0
0,5
1,0
1,5
2,0
2,5
3,0

Measurement inside 3mm cooling canal
MEASUREMENTS on TURBINES

Measurements of $T$ et $\rho$ at 30 kHz
Ageing diagnostic on motor divergent

Axial profile

Radial profile
Ageing control of ball bearing surface in cryogenic conditions

APPLICATION ON ROCKET MOTOR
CONTROL for COMPOSITE BRAKE TESTS

T measurements

ρ measurements: surface state
ON LINE MEASUREMENT OF SHEET IRON GALVANISATION
APPLICATION on H.T-X.R.D. CHAMBER

In situ characterization of surface at high temperature by using simultaneously a pyroreflectometer and an diffractometer. Applied Surface Science, V135, p 91-96, 1998