Environmental Thermography

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Thermography

Definition: the infrared thermography deals with the acquisition and analysis of the thermal information coming from physical bodies and acquired with remote sensing devices (***without contact***)

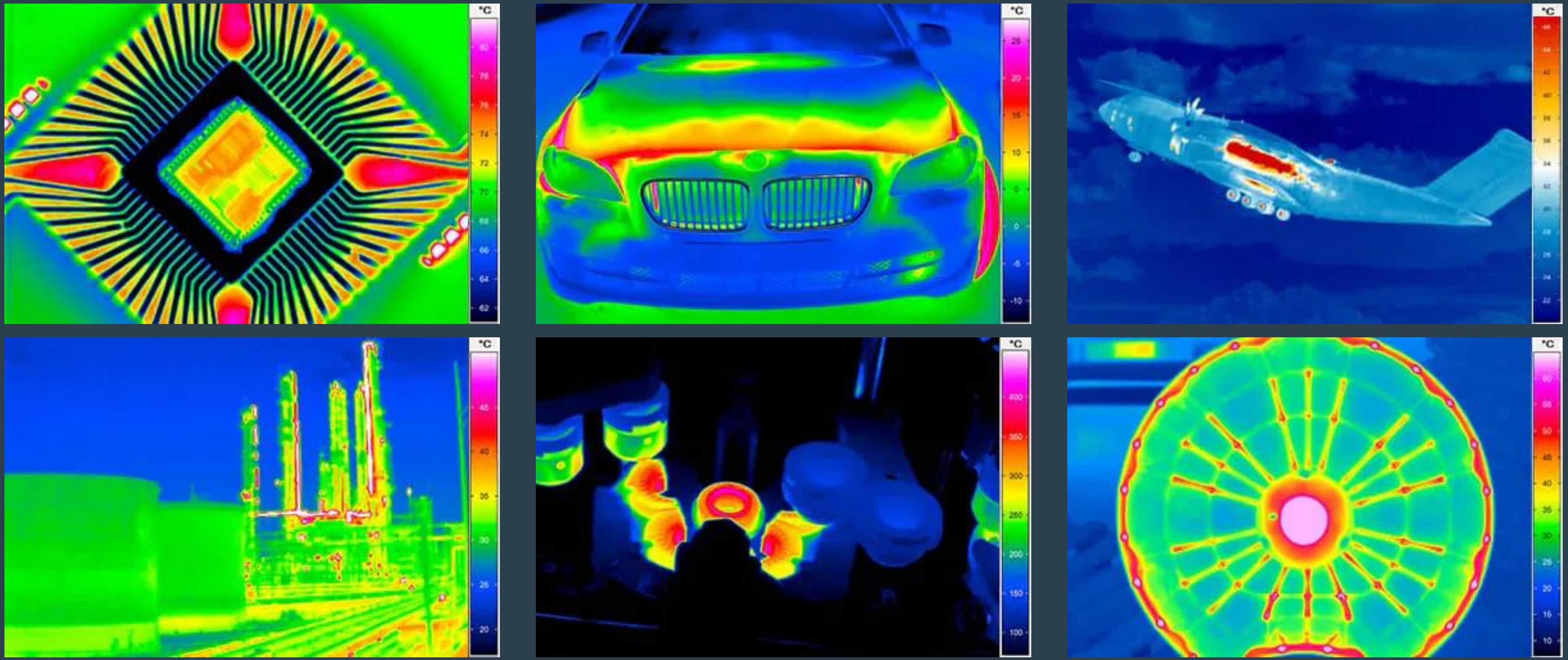
The infrared camera is the remote sensing device that reads the emitted radiation from the ***surface*** of a physical body (input) and converts it into a radiative temperature (output)

Thermography

- No-contact sensing
  - Do not modify the object status
  - Do not perturb the measurement
- Bi-dimensional
  - The acquired image can be further modified and analyzed within certain limits
- Real time
  - Snapshot of stationary thermal schemes
  - Snapshots of transitory stages

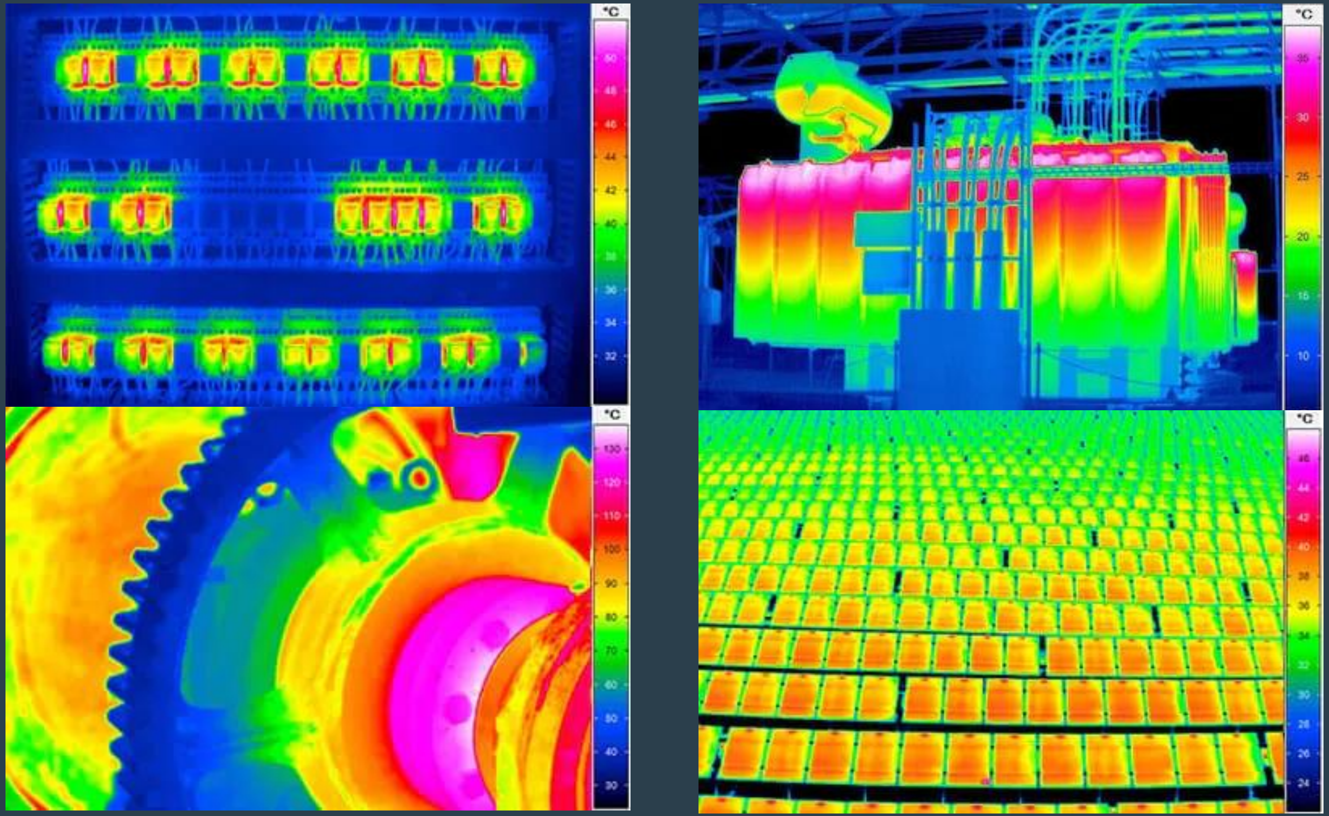
Example of Thermography Applications

Industry: Car, Metallurgical, Chemical, Aerospace, Industrial, Plastic, Glass, Electrotechnical



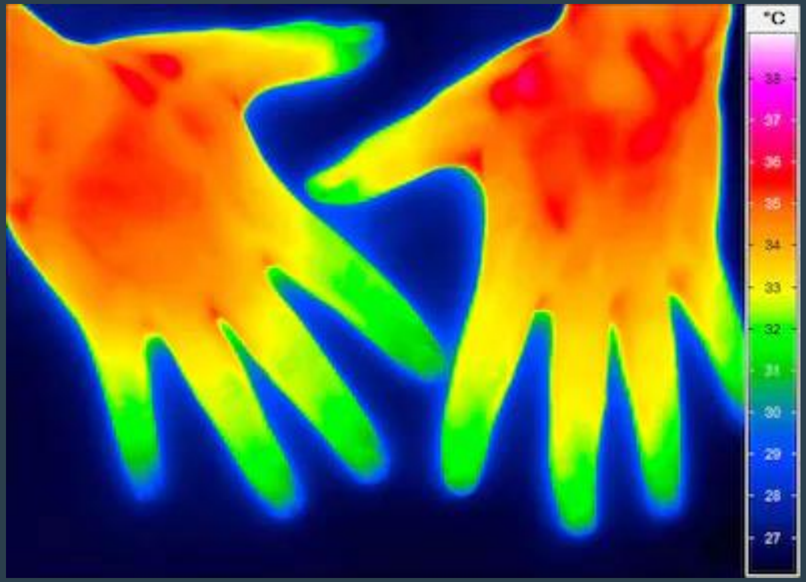
Example of Thermography Applications

<u>Energy sector</u>: mostly used for the identification of malfunctions, troubleshooting, and optimization



Example of Thermography Applications

Medicine: identification of anomalies in the human body and diagnosis of different pathologies



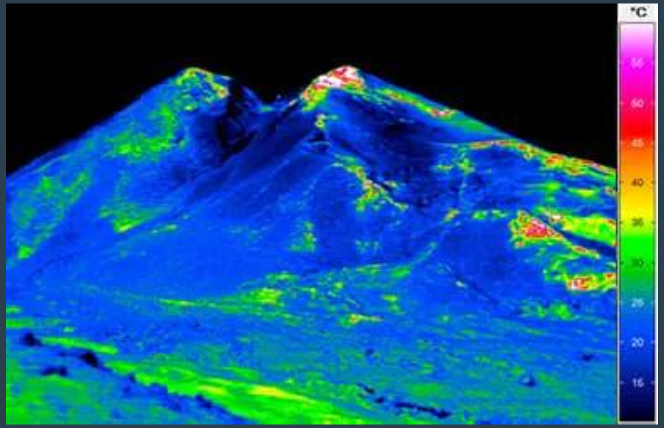
Example of Thermography Applications

Agriculture

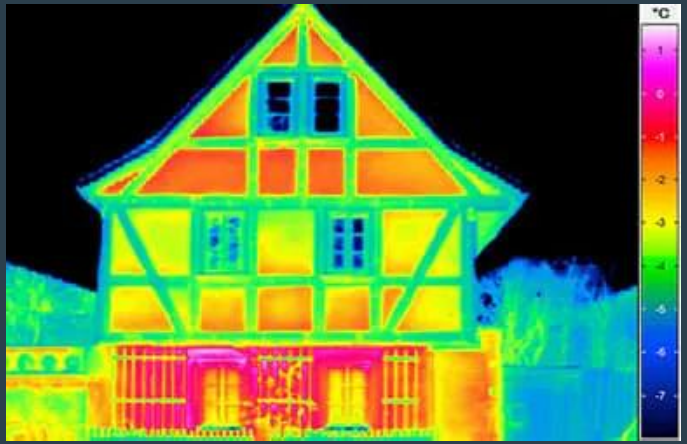
Thermography to assess the health condition of agricultural fields, cultivations and livestock. Support production and problem individuation.

Biology and Geology

Analysis of surface heterogeneities, daily cycles of surface heating, natural and anthropogenic heat sources.



Example of Thermography Applications

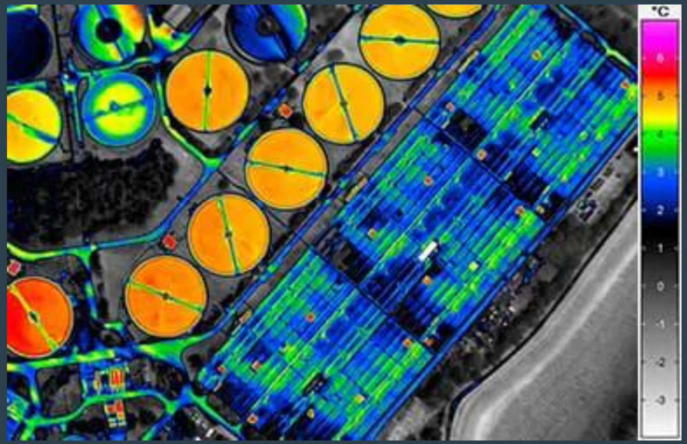


Construction Industry

Façade and rooftop integrities, heat and water leaks. Thermal forcing of the building on the environment

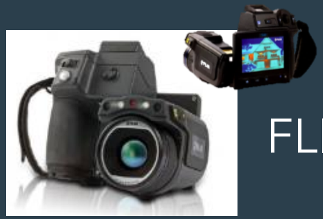
Areal Thermography

Geological evaluation, environmental damage evaluation, surface heat island effect computation.



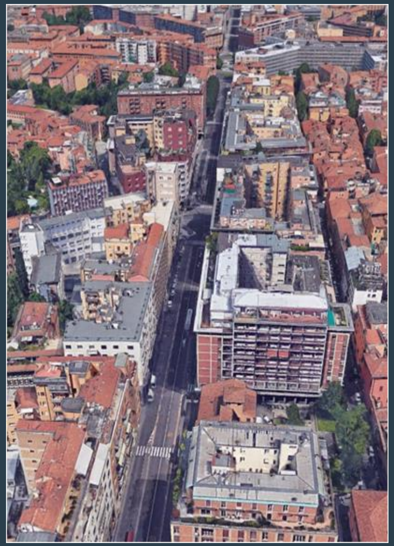
Application in Bologna: SUHI estimation

Thermographic campaign



FLIR T620

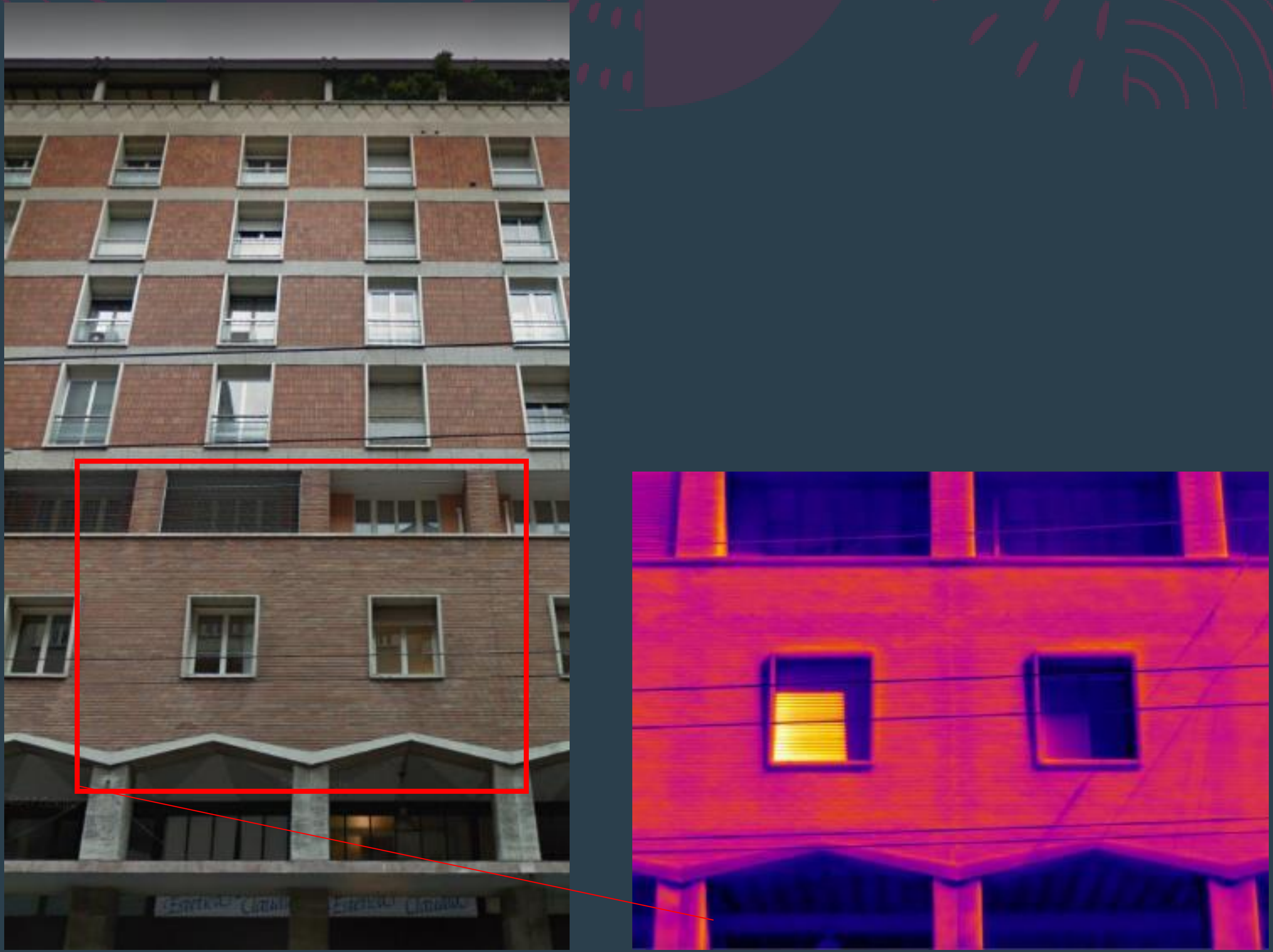
- *Scope:* Measure the surface temperature of building facades and street pavements within two urban canyons
- *Setup:* 2 man-handled thermal cameras working simultaneously
- *Measure:* 24-hour experiment with measurements of 10 selected buildings (plus the street) once every two hours



Via Marconi
- H = 33m, W = 20m
  H/W = 1.65
- Downtown, 4 lanes
- No trees
- ZTL, autobus, pedestrian
- Densely built-up area

Via Laura Bassi
- H = 17m, W = 25m
  H/W = 0.7
- Residential area, 2 lanes
- Trees
- No ZTL, private cars, pedestrian, cycle
- Single houses or buildings, gardens

Position 1: Via Marconi, 31 - facing west (Marconi P1W)
04:00 pm - 22/08/2017



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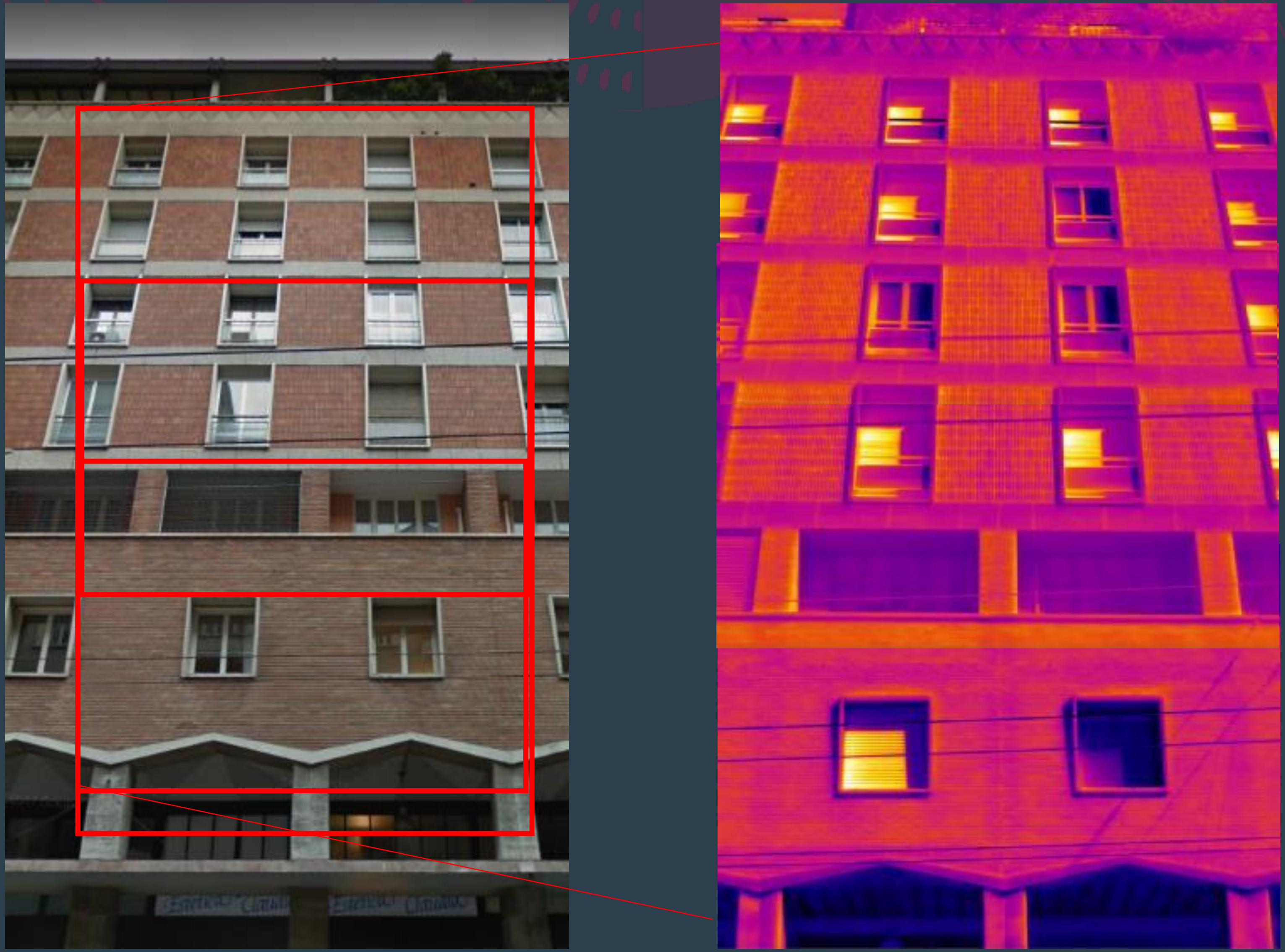

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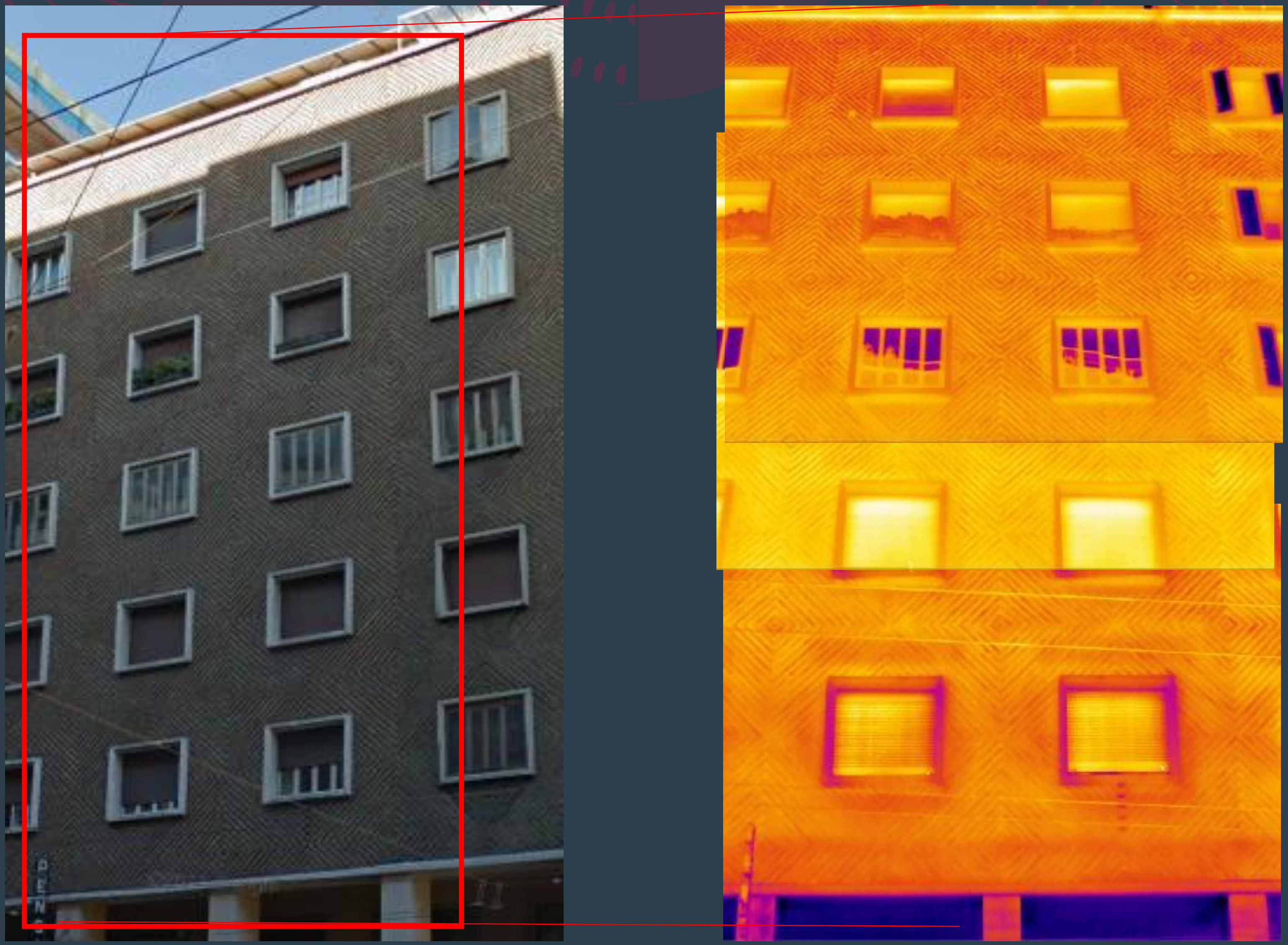

Position 5: Via Marconi, 24 - facing east (Marconi P5E)
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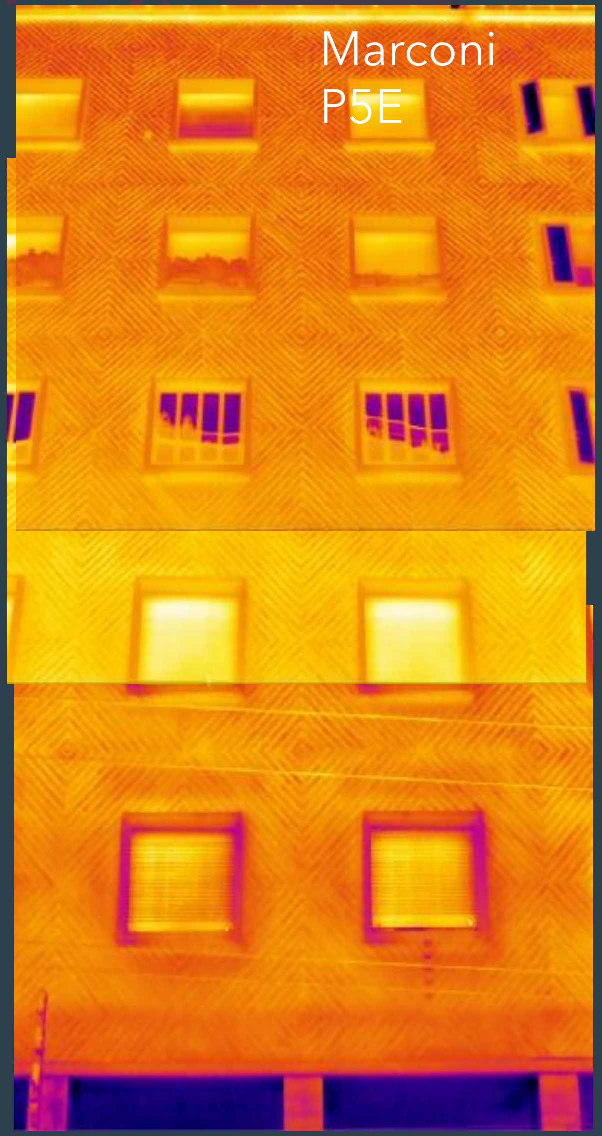

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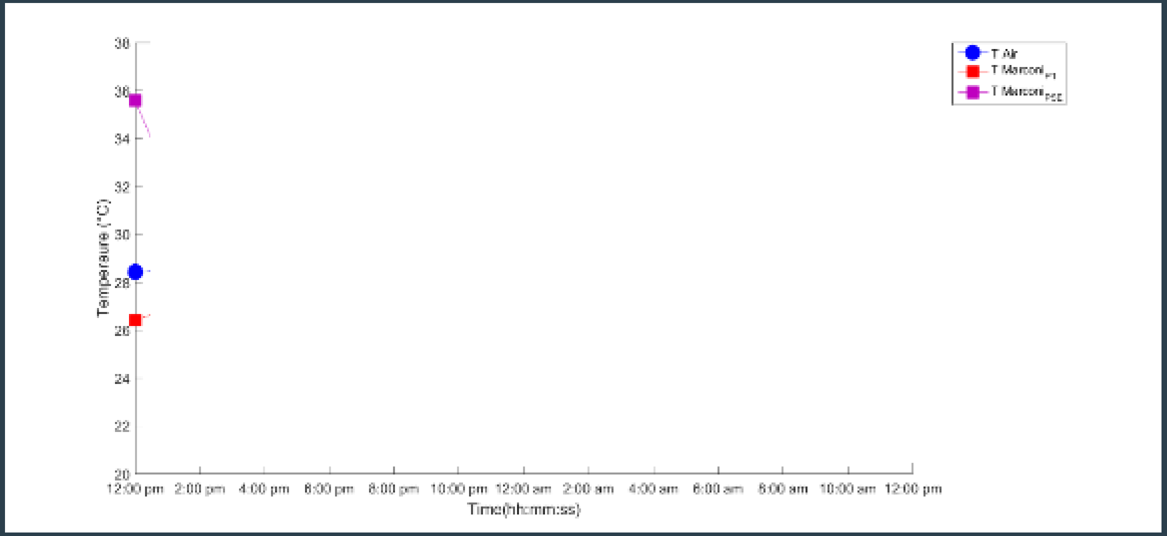

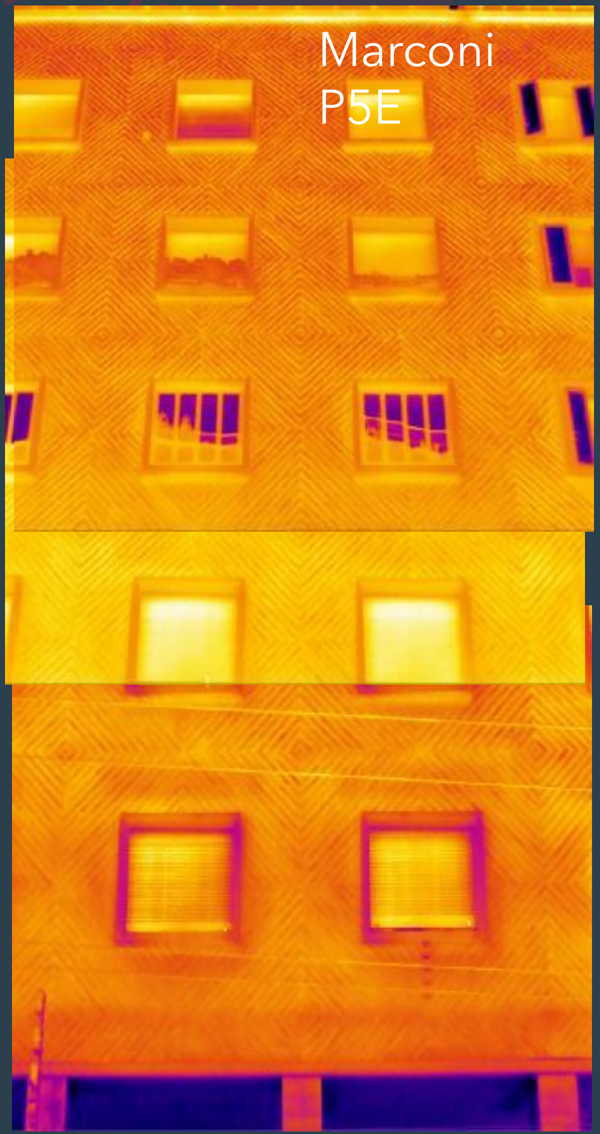

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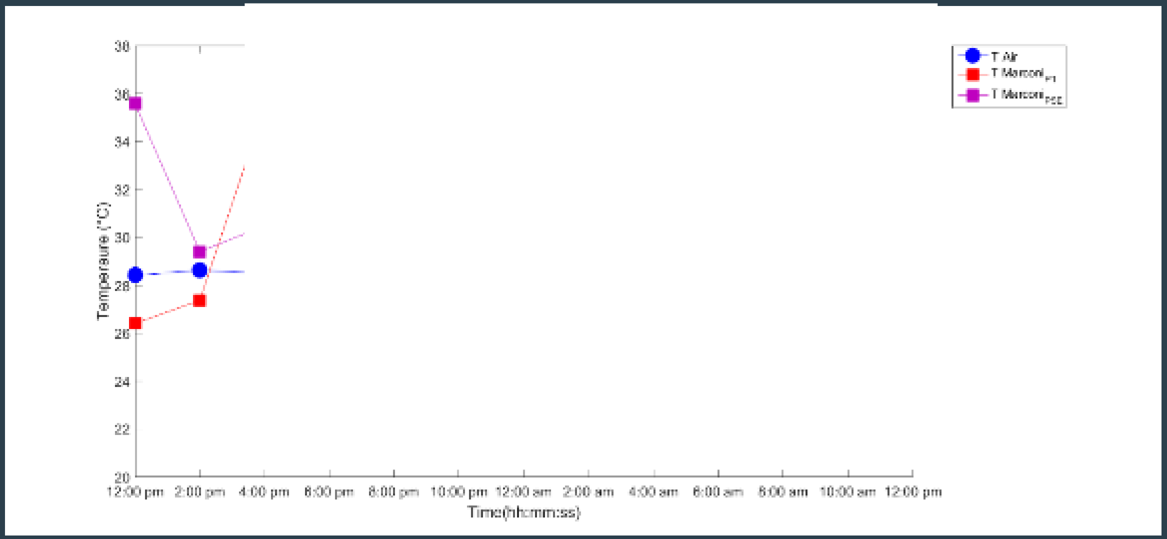

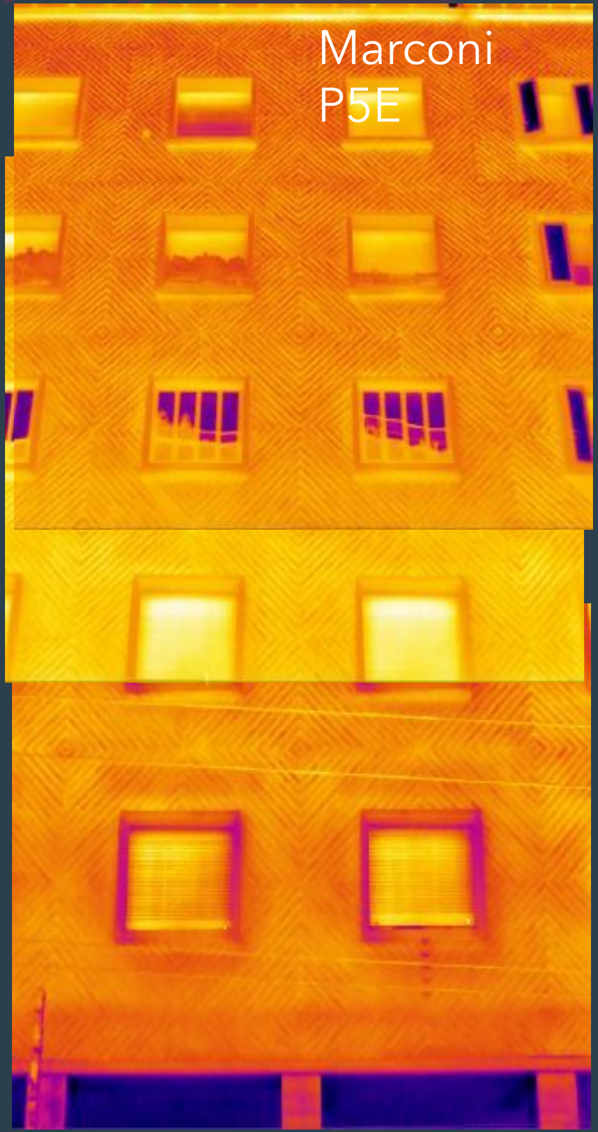

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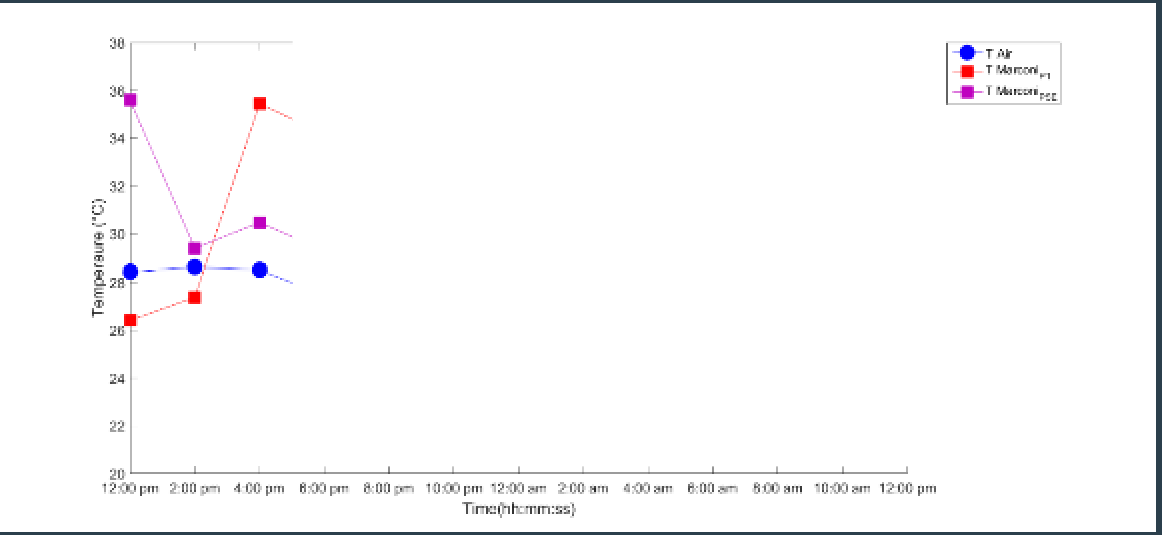

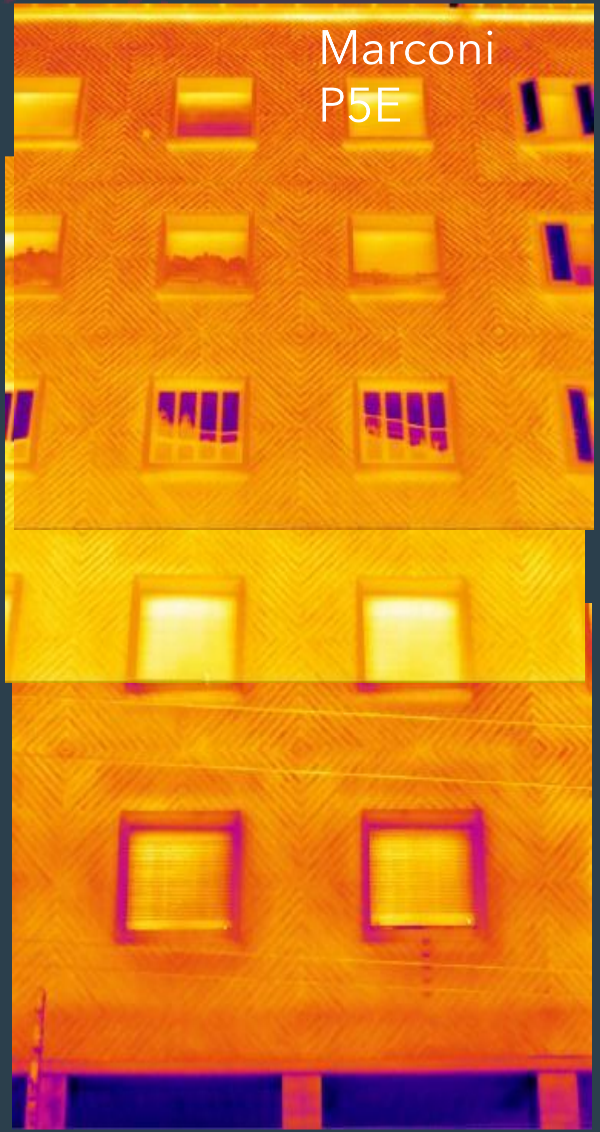

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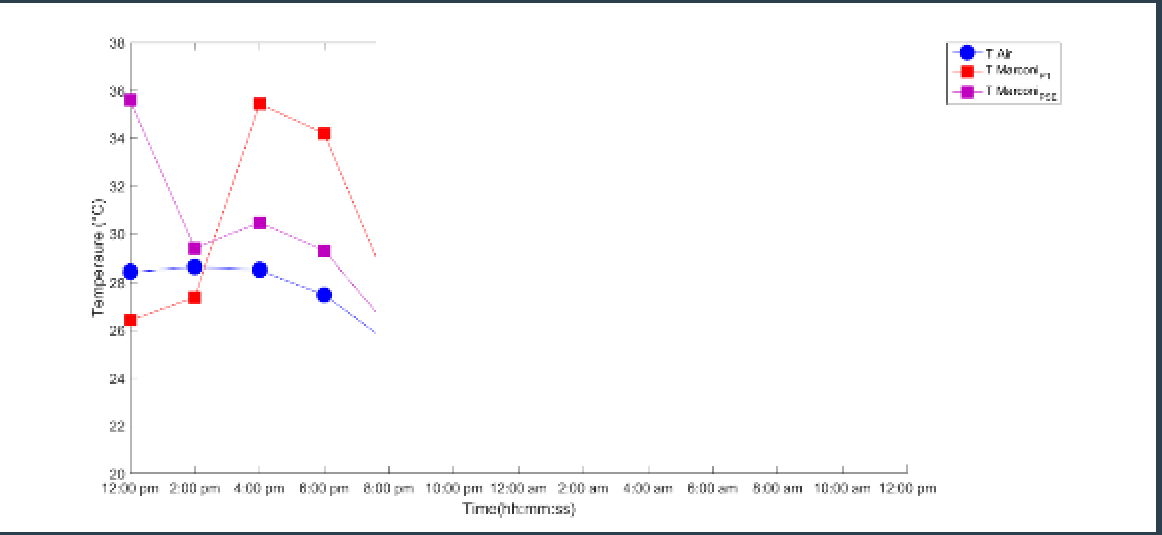

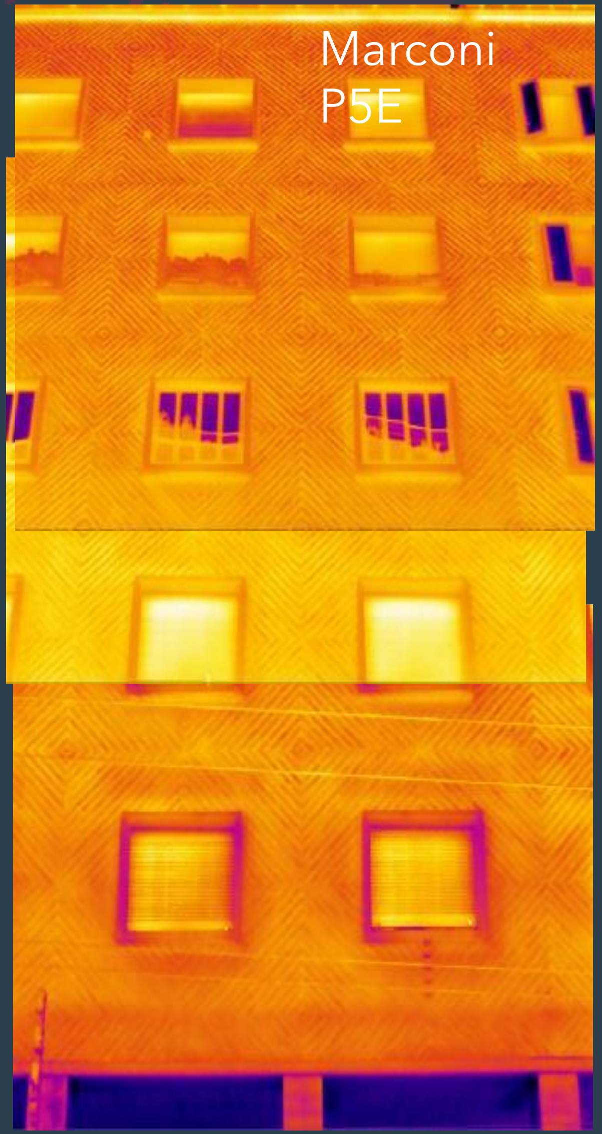

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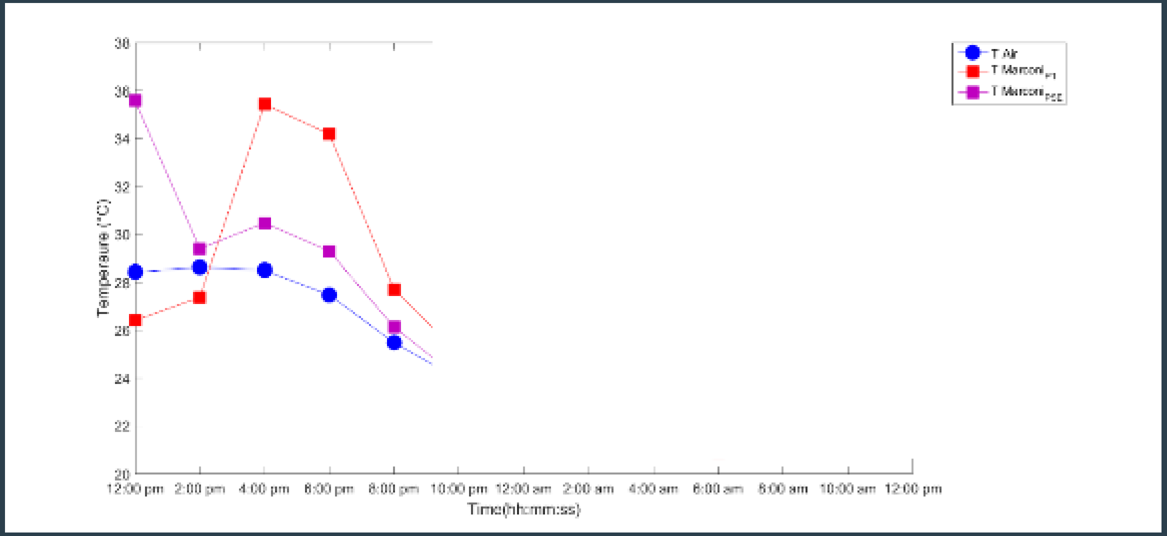

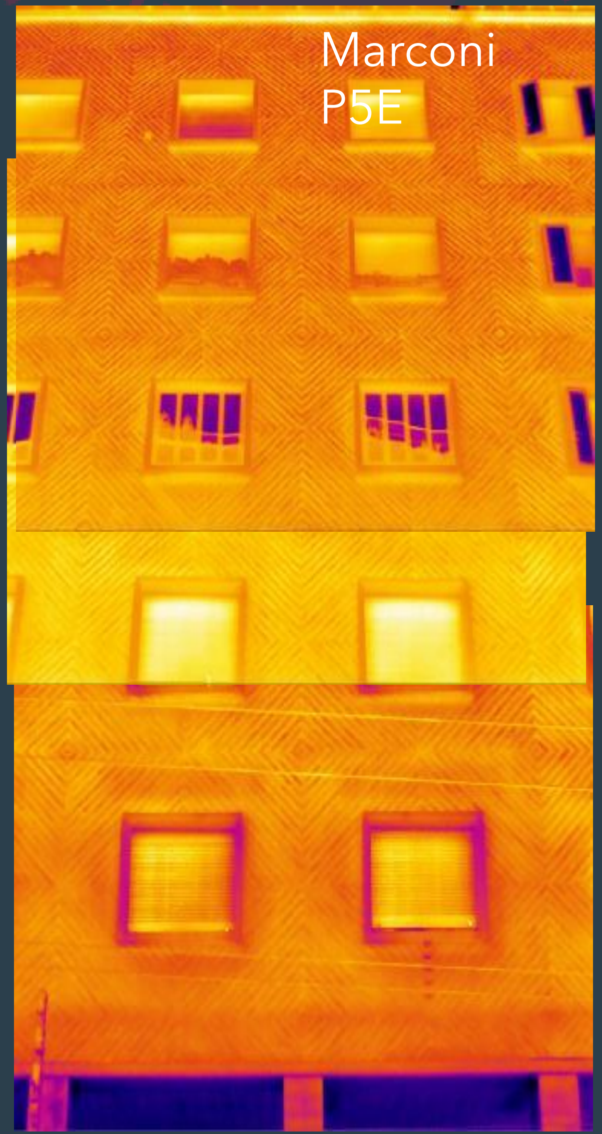

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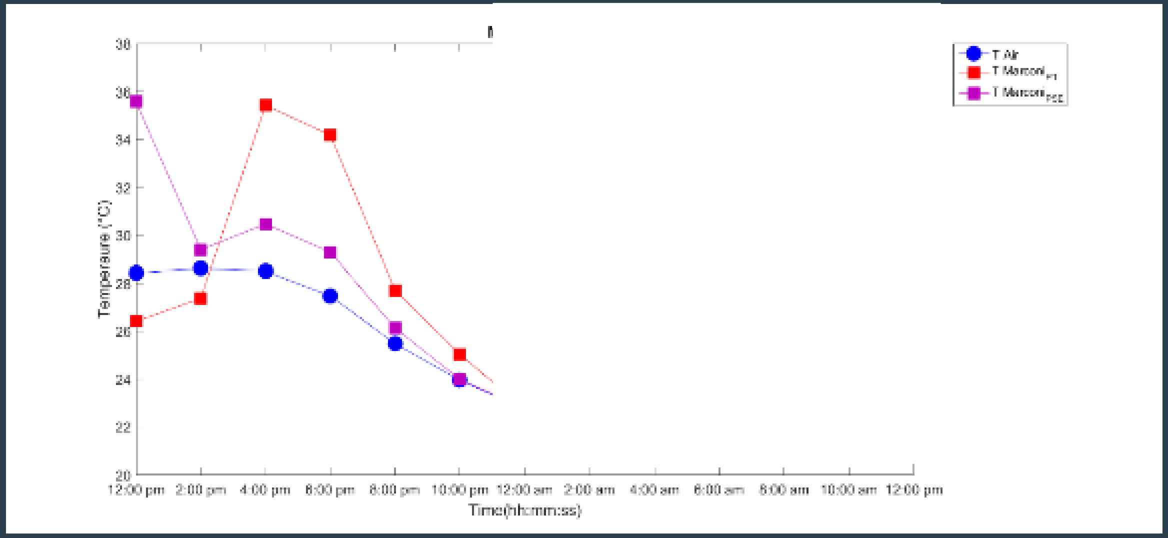

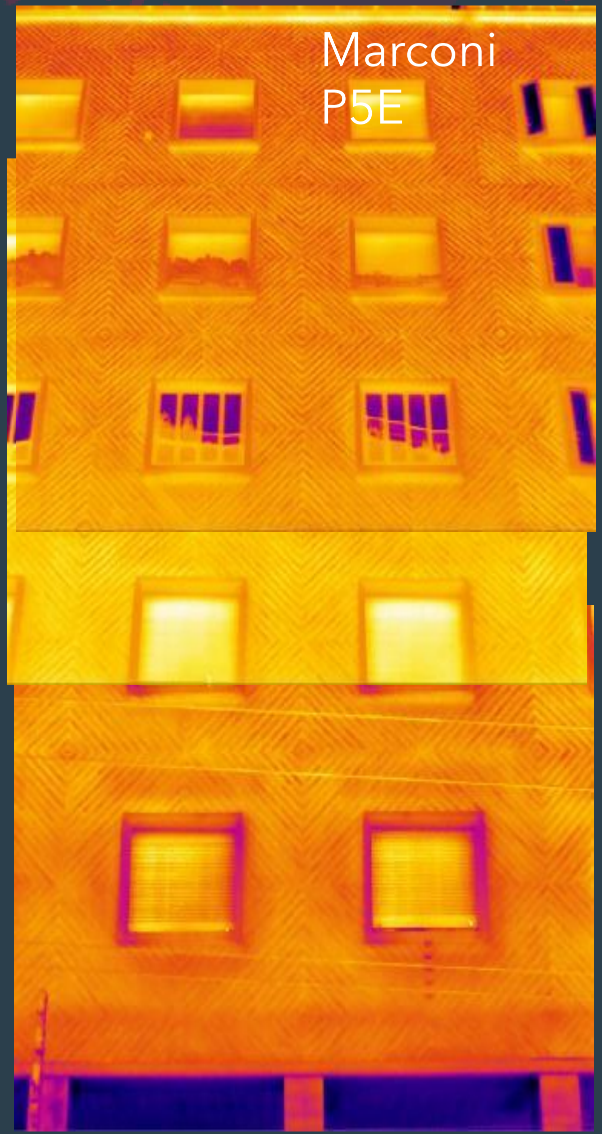

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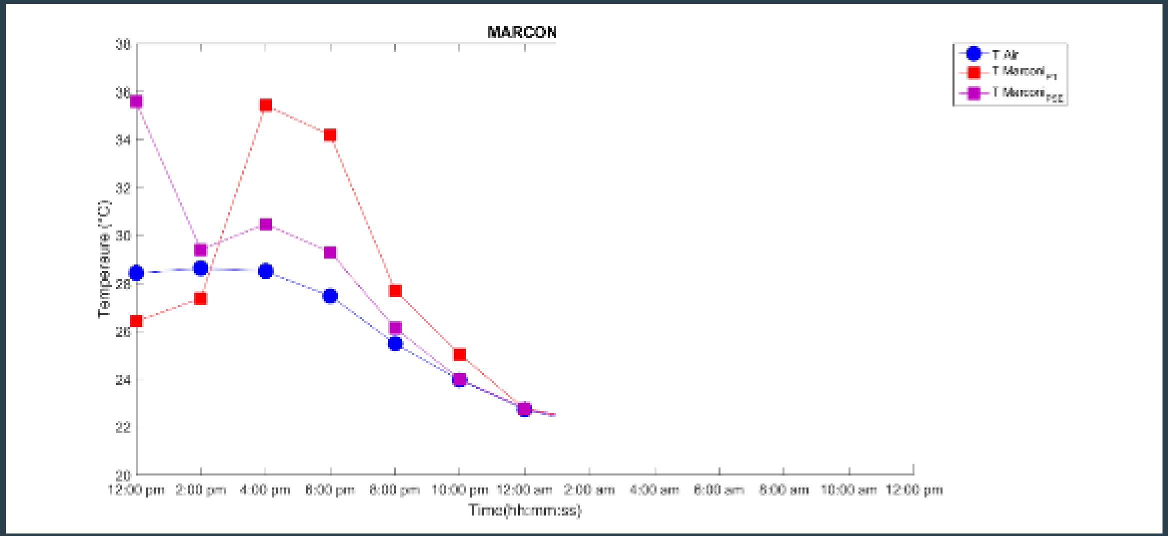

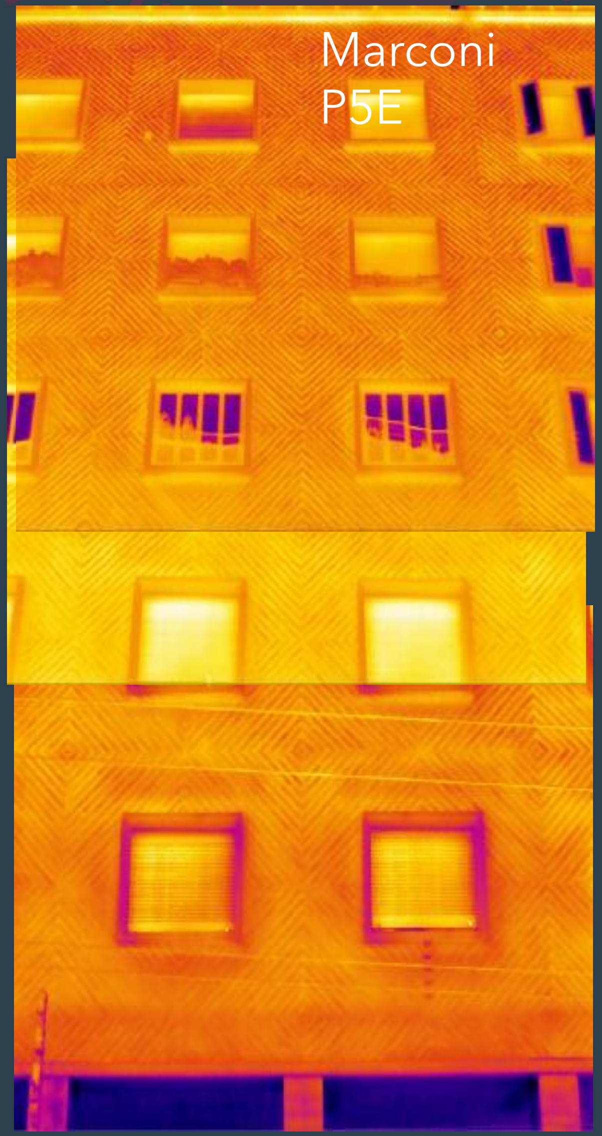

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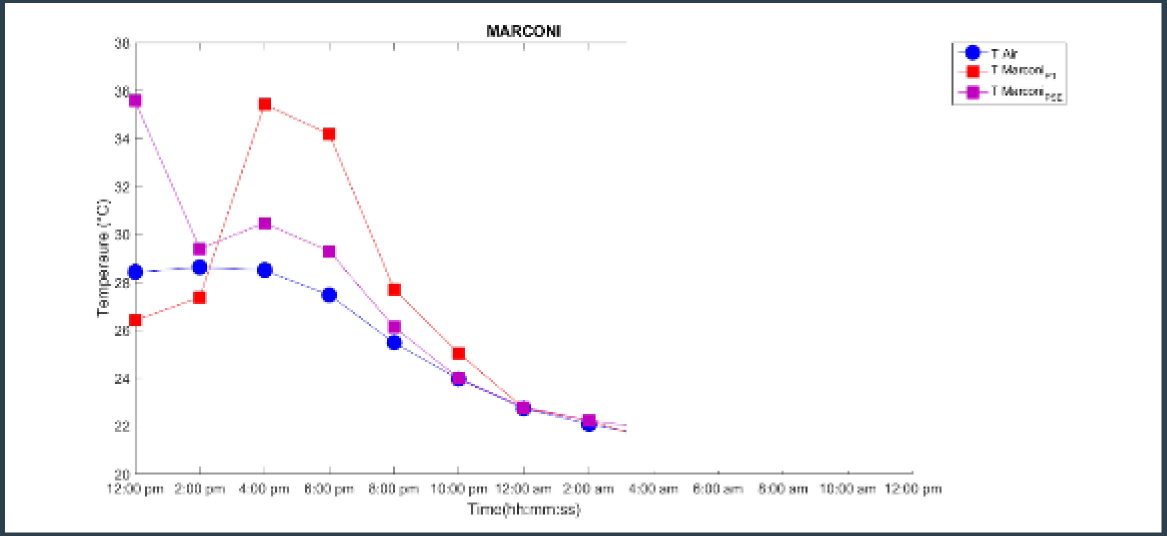

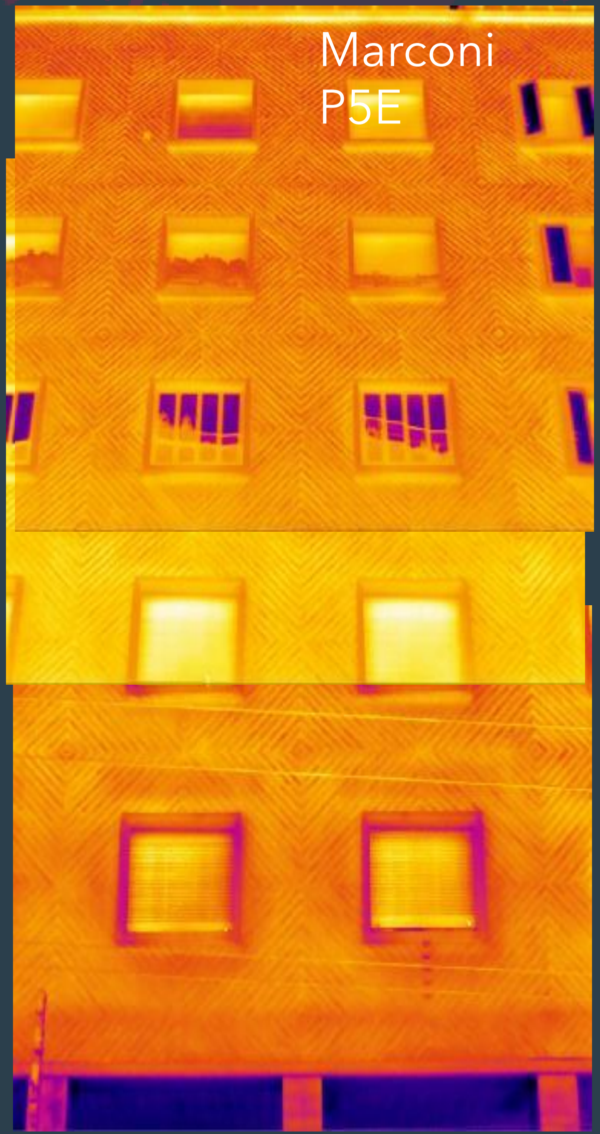

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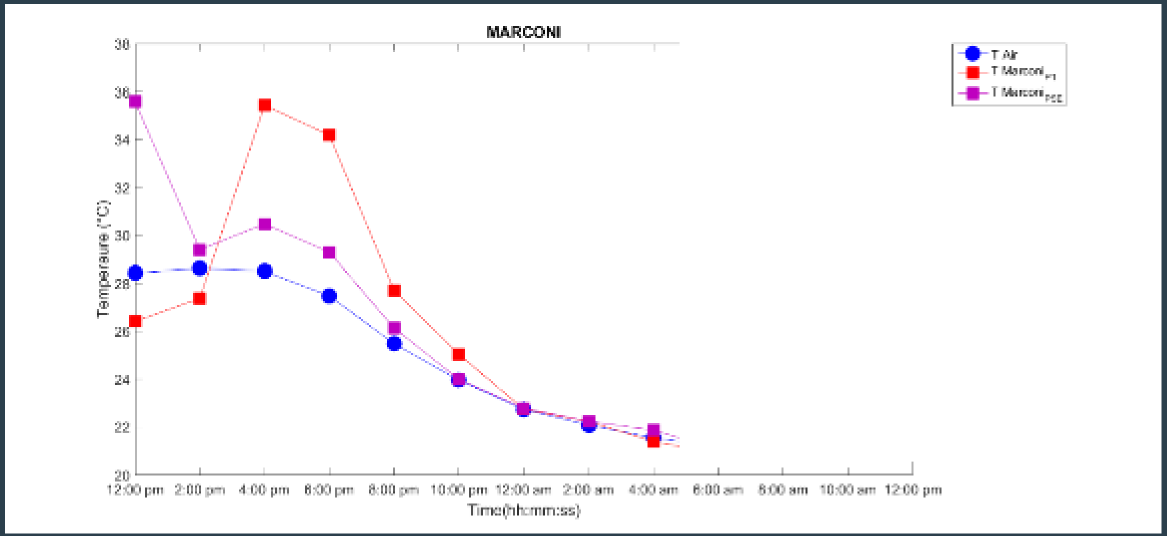

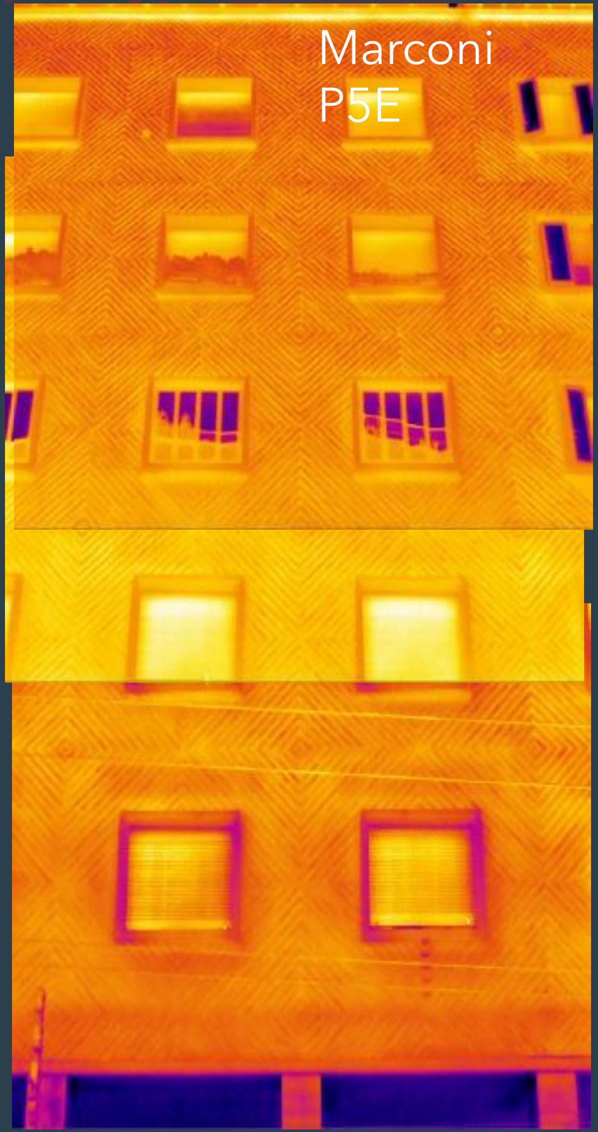

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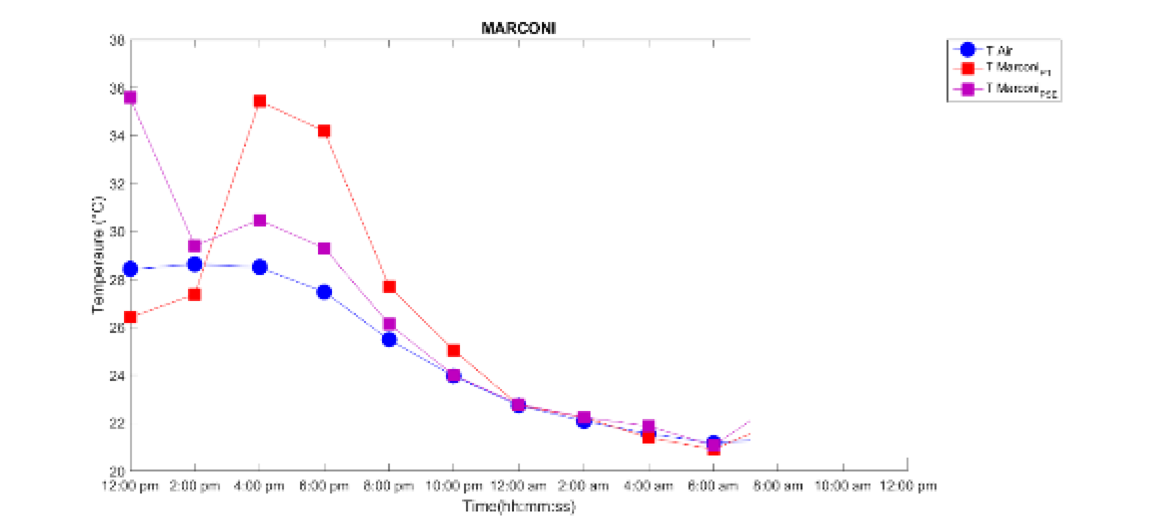

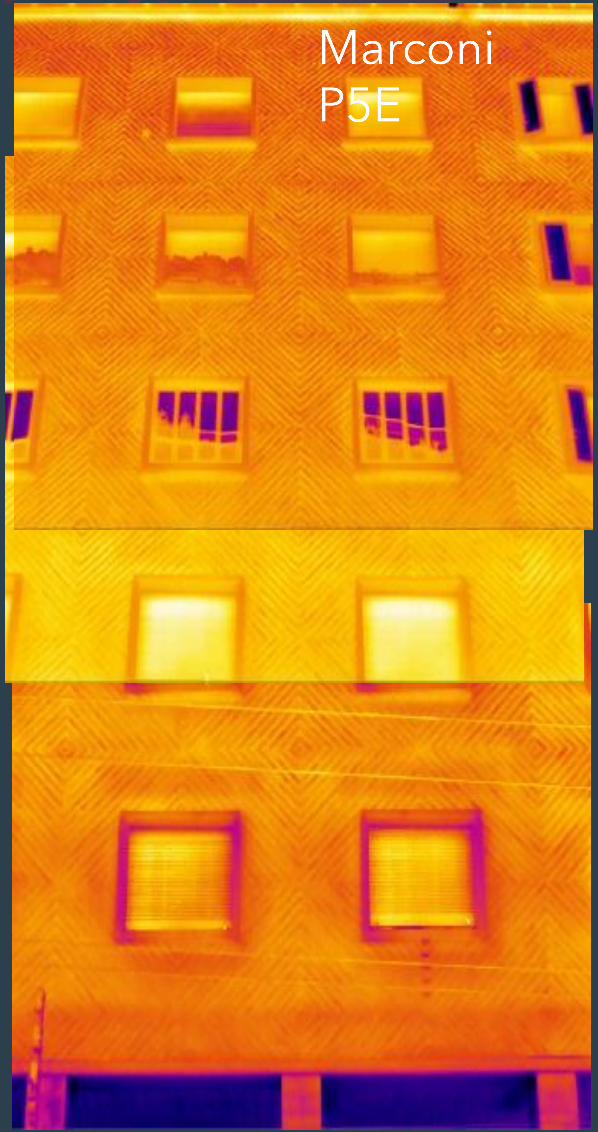

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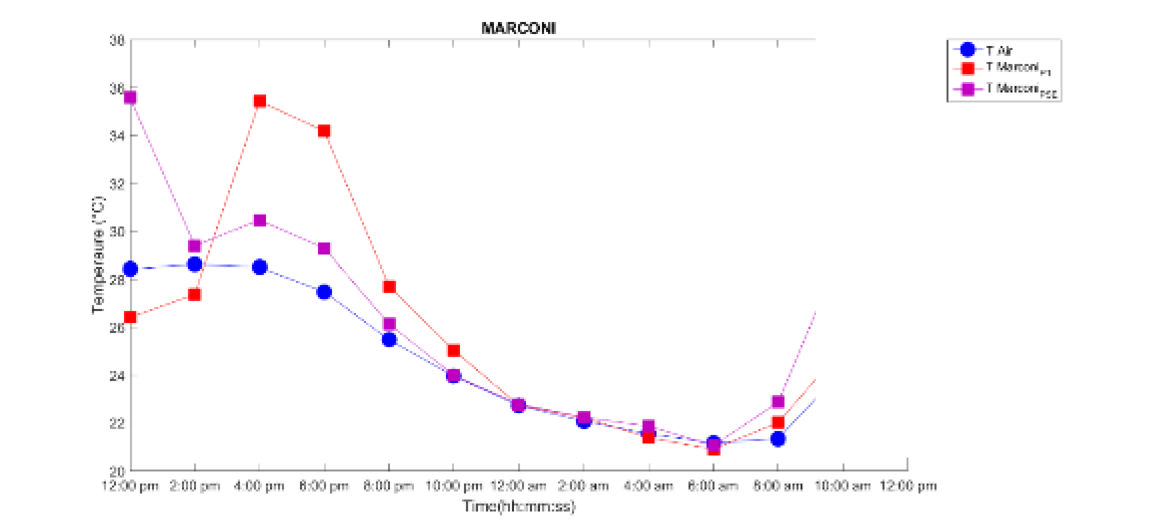

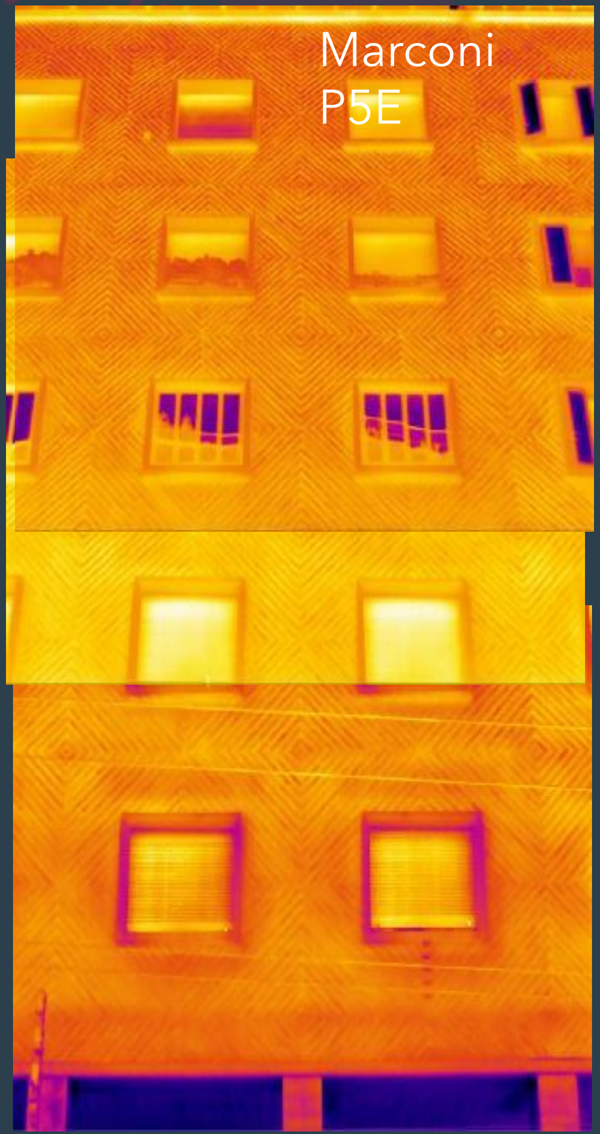

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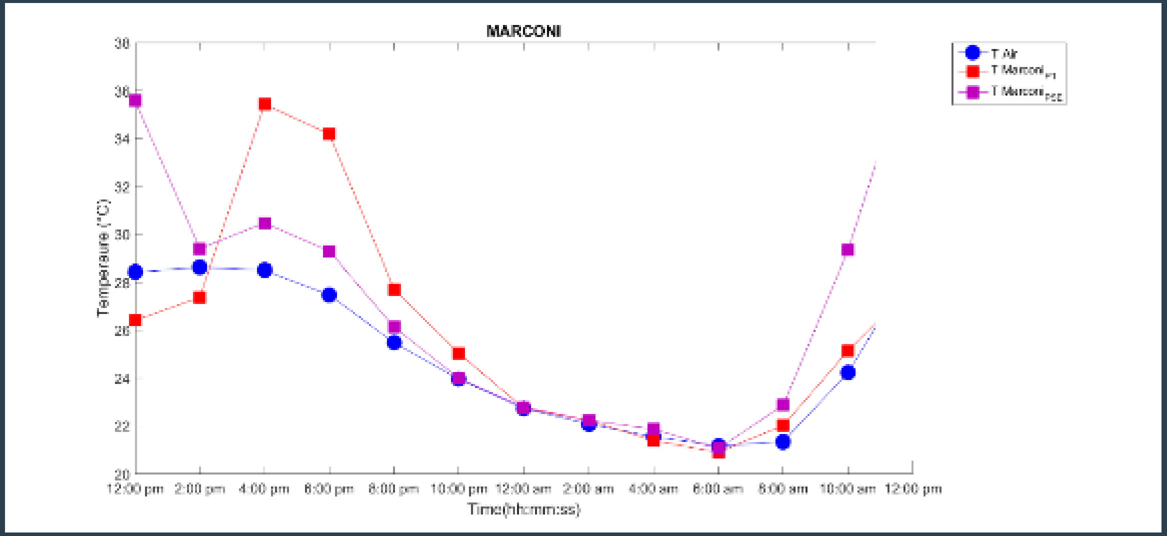

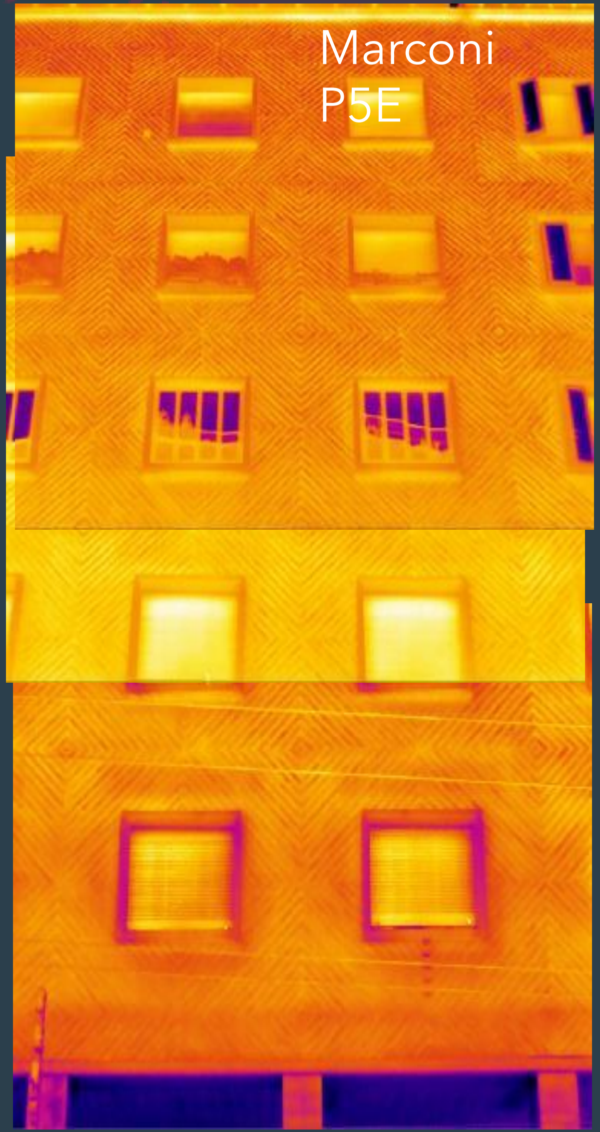

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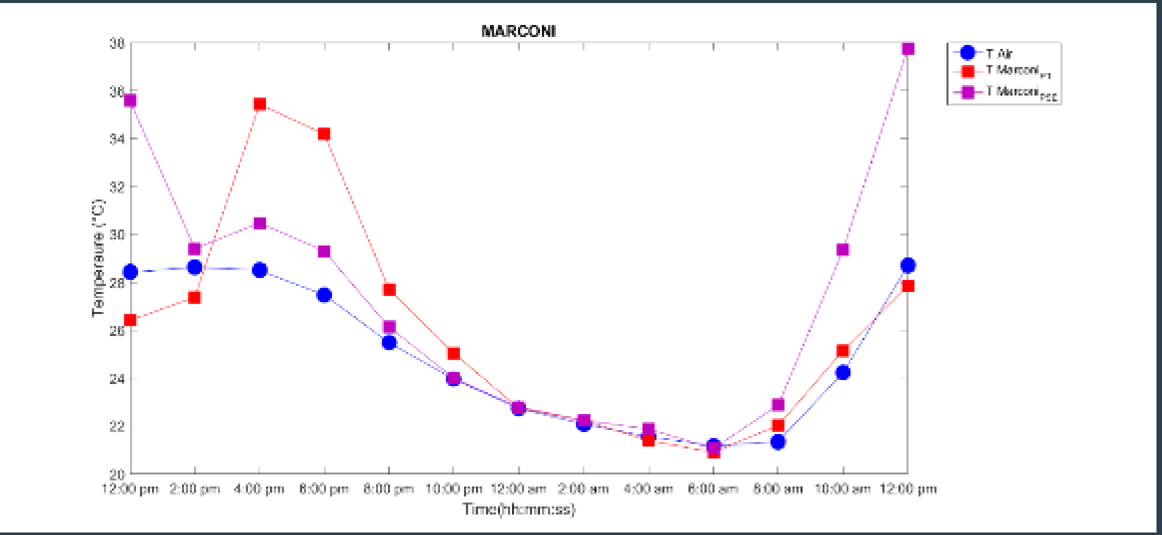
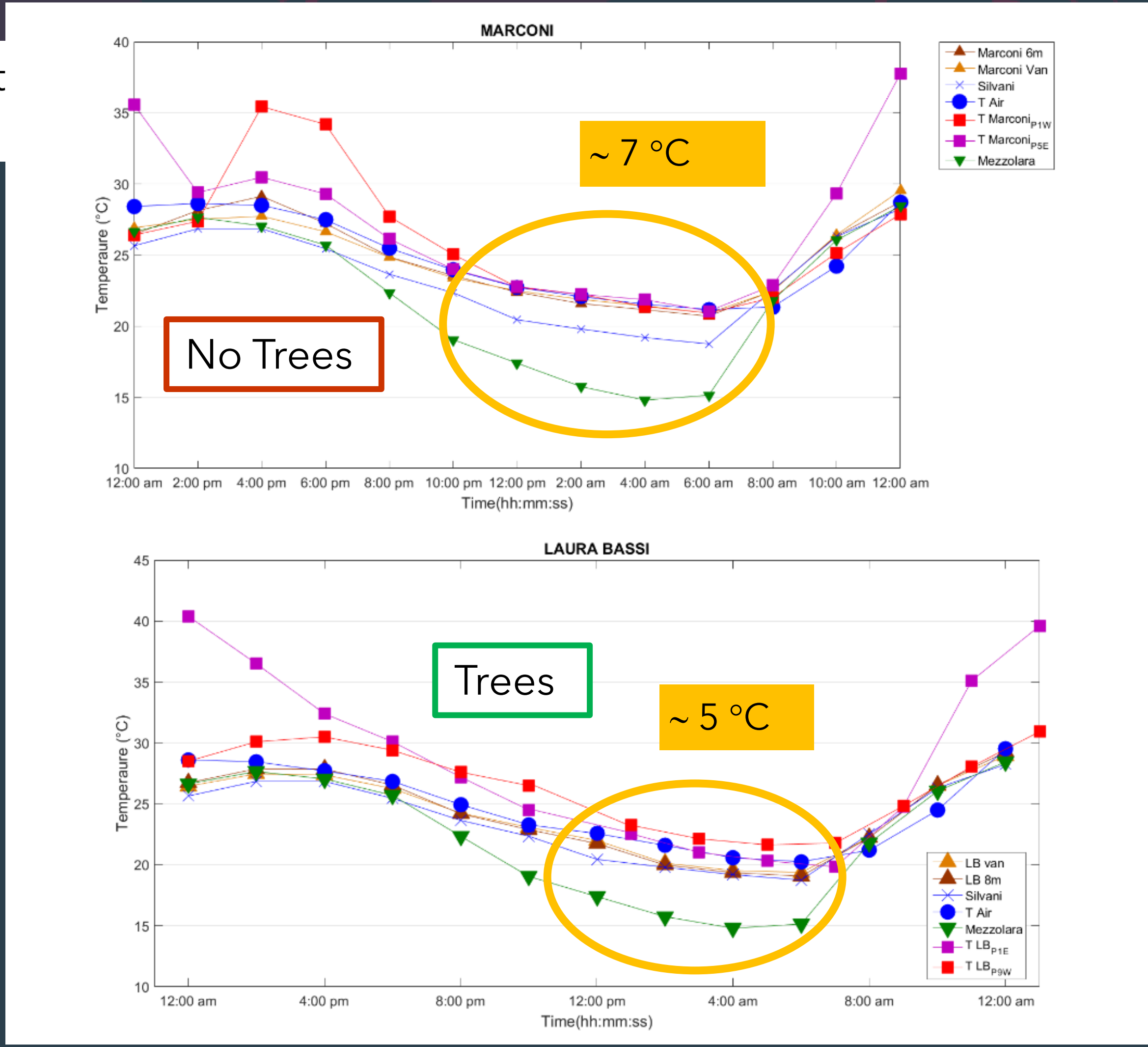
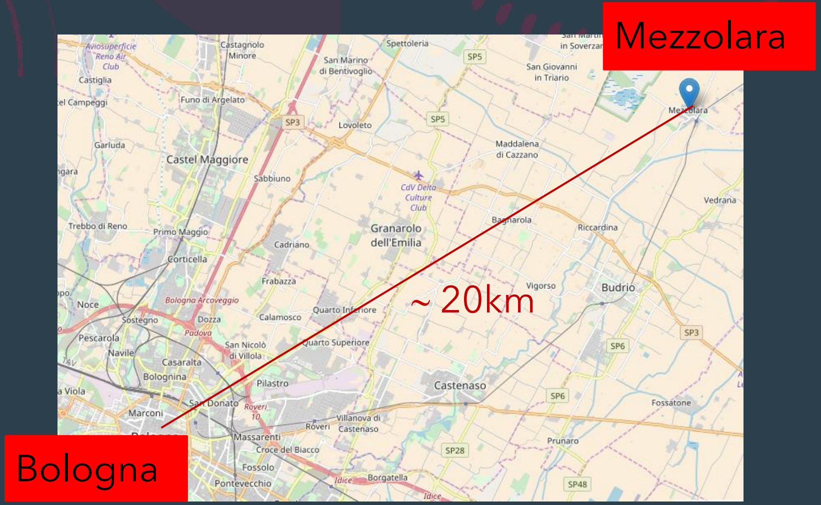


Di Sabatino et al., 2020





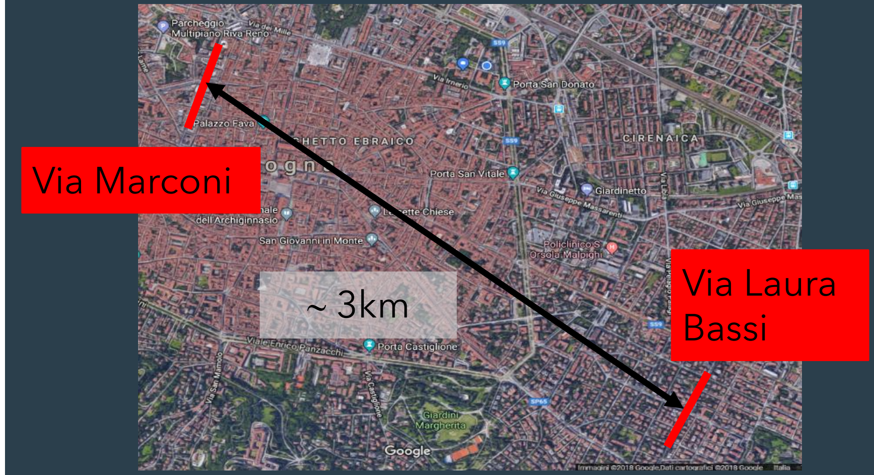


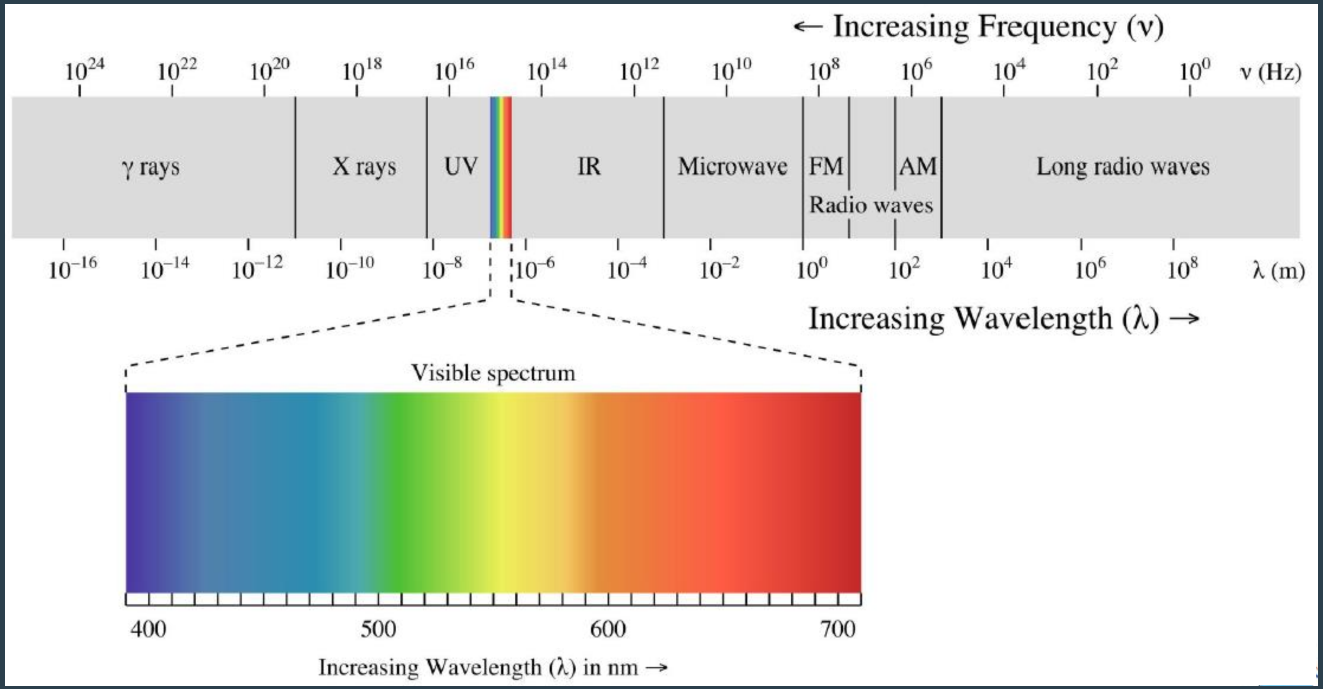
Fig. *(**Top**) Temperature evolution at different locations within Marconi St., city and rural references. (**Bottom**) Temperature evolution at different locations within Laura Bassi St., city and rural references*

Radiation

For thermography, the most impactful portion of the body radiation spectrum ranges at the **infrared wavelength,** where everyday bodies emit

Solar radiation has dominant frequencies in the shortwave ($\lambda < 4\ \mu m$) while terrestrial radiation is centered in the longwave ($\lambda > 4\ \mu m$)

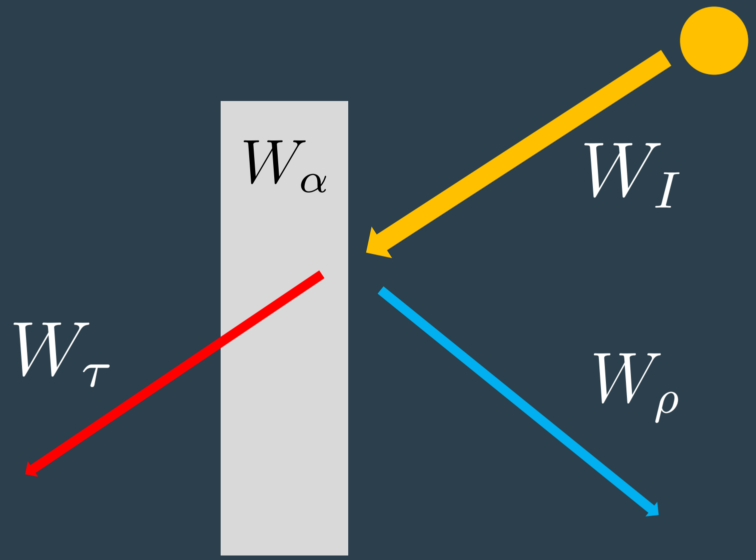
Our cameras operate in the far infrared (LW=long wavelength), between 7.5 and 14 micrometres



Basic laws of radiative transfer

The incident radiation (i.e., the total radiation coming from multiple sources and impacting the object) is partitioned into absorbed, reflected and transmitted components when impacting an object

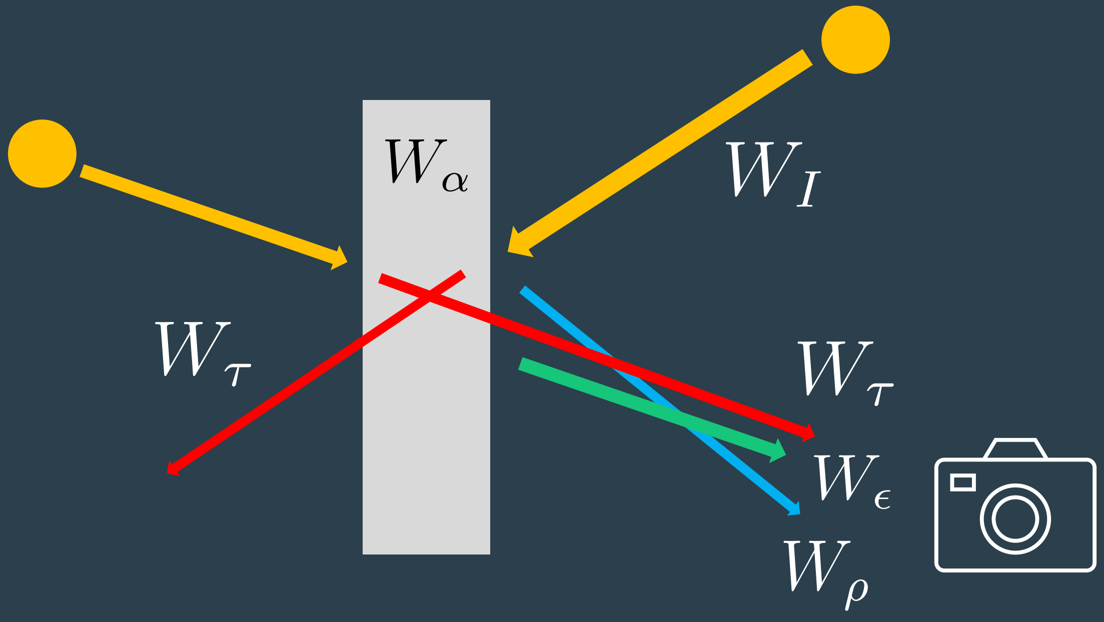
$$W_\alpha + W_\rho + W_\tau = W_I = 100\%$$



Basic laws of radiative transfer

The radiation measured by the camera is the sum of all the components coming from all the possible sources in the ambient. If we can isolate (with reasonable assumptions) the body of our investigation, we have

$$W_\epsilon + W_\rho + W\tau = W_{meas} = 100\%$$



Blackbody Radiation

A **blackbody** is a body that is characterized by:

- Complete absorption of all incident radiation
- Maximum possible emission in all wavelength in all directions

The monochromatic radiance emitted from a black body is determined by the sole temperature of the black body as defined by the **Planck Law (Planck function):**

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5(e^{hc/k\lambda T} - 1)}$$

$h = 6.626\ x\ 10^{-34}\ Js$ (Planck constant)

$c = 2.998\ x\ 10^{8}\ ms^{-1}$ (light speed)

$k = 1.381\ x\ 10^{-23} JK^{-1}$ (Boltzman constant)

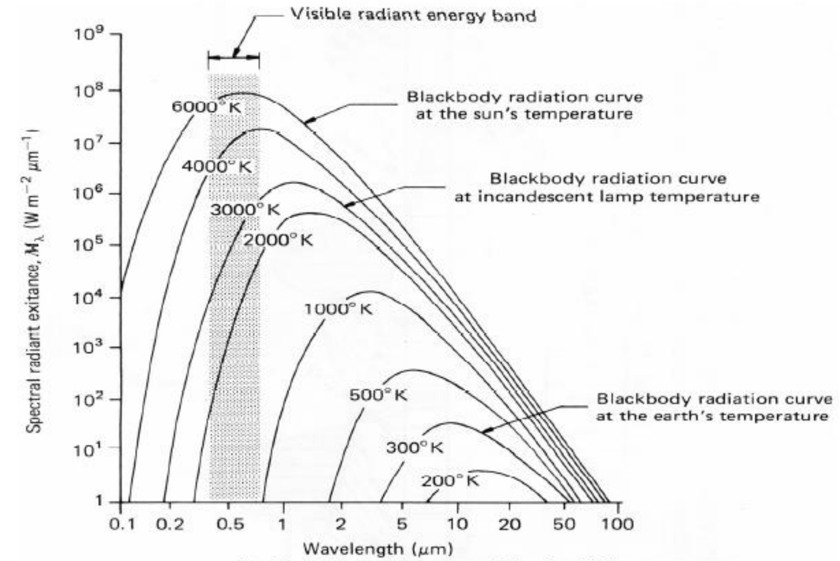


Fig. 3-3 Blackbody radiation curves (taken from HJB).

How radiation interact with bodies

- Absorption (α): capacity of a body to capture and contain radiation changing its internal properties
- Emission (ε): capacity of a body to emit the radiation
- Reflection (ρ): capacity of a body to irradiate the incident radiation without absorption at the same angle of incidence (reflection or symmetrical scattering + in all directions diffusive scattering)
- Transmittance (τ): capacity of a body to be passed by radiation

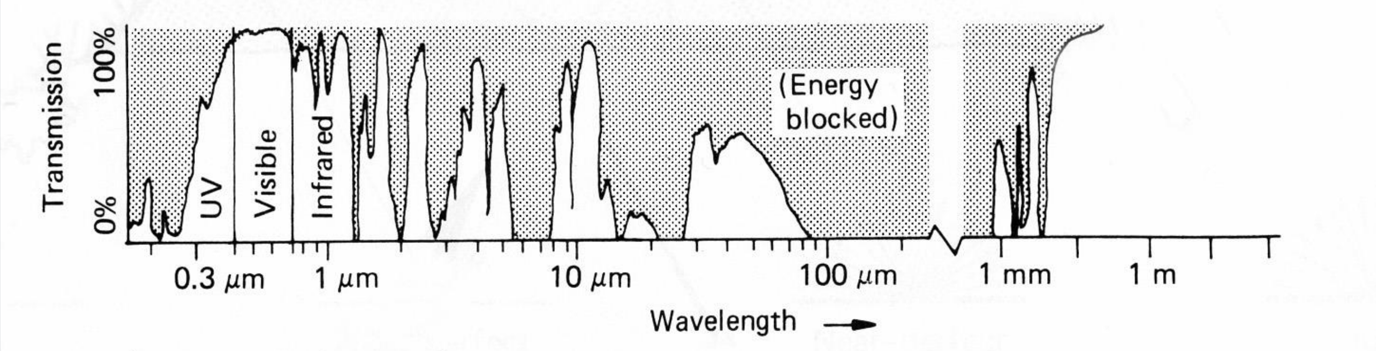
Transmission

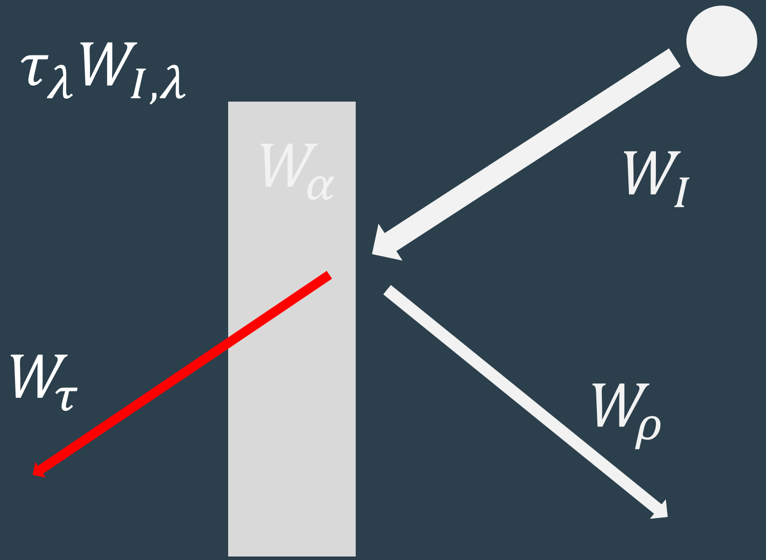
Transmission is the capacity of a body to be passed by radiation without interacting with it.

The capacity of the body to transmit radiation is quantified by the **transmission coefficient (or transmittance)** $\tau_\lambda \in [0, 1]$:

- A perfect window has $\tau_\lambda = 1$
- An opaque body has $\tau_\lambda = 0$

The transmitted fraction of incident radiation is $W_{\tau,\lambda} = \tau_\lambda W_{I,\lambda}$

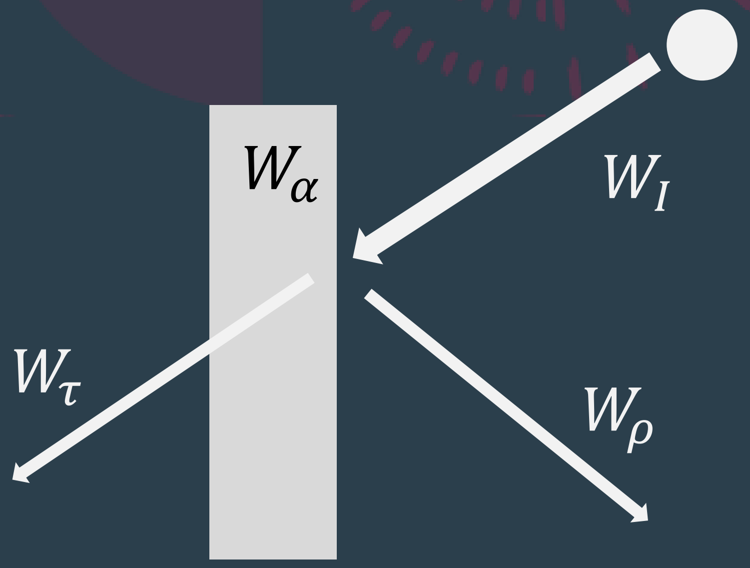




Absorption

Absorption is the capacity of a body to capture the photons of the incident radiation and convert their energy in internal energy or heat.

Absorption occurs only if the energy of the photon corresponds to the energy required to the molecule to reach a state of excitation. If absorption is not possible, reflection or transmission will occur.



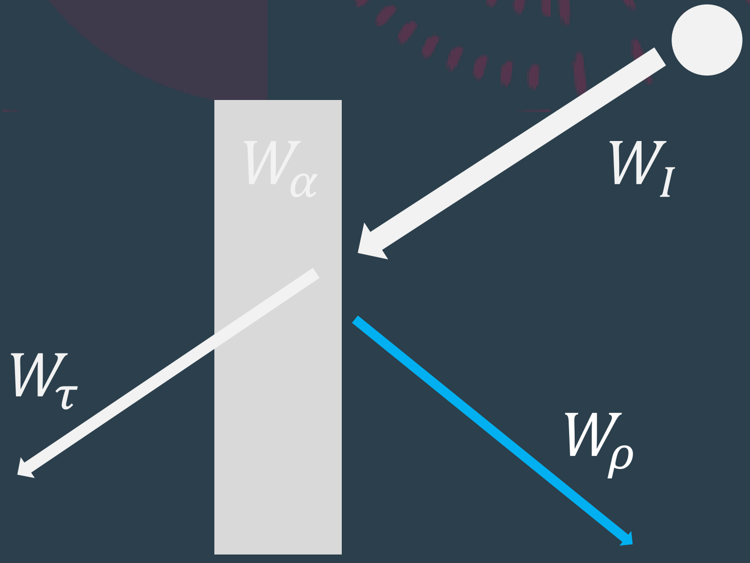
The capacity of the body to absorb radiation is quantified by the **absorption coefficient (or absorbance)** $\boldsymbol{\alpha_\lambda} \in [\mathbf{0}, \mathbf{1}]$:

- A blackbody has $\alpha_\lambda = 1$
- A perfect window has $\alpha_\lambda = 0$

The transmitted fraction of incident radiation is $W_{\alpha,\lambda} = \alpha_\lambda W_{I,\lambda}$

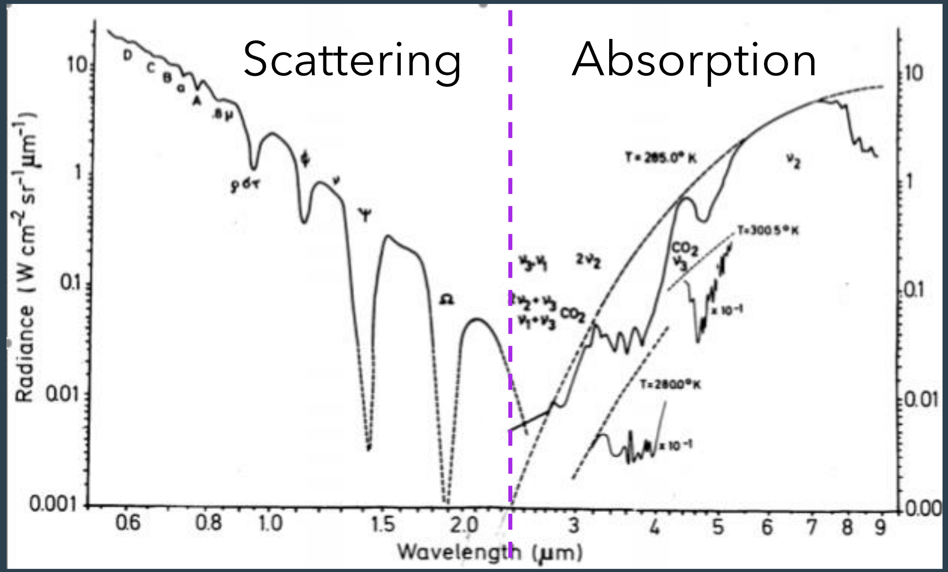
Scattering (reflection)

Incident waves from some source excite **secondary waves** from the scatterer (a parcel of matter) and the superposition of all these waves is what is observed.



The capacity of the body to reflect radiation is quantified by the **reflection coefficient (or reflectance)** $\boldsymbol{\rho_\lambda \in [0,1]}$:

- A perfect mirror has $\rho_\lambda = 1$
- A black body has $\rho_\lambda = 0$



The reflected fraction of incident radiation is $W_{\rho,\lambda} = \rho_\lambda W_{I,\lambda}$

Emission

The radiance emitted by a body is

$$W_\lambda = \epsilon_\lambda B(T)$$

where $B(T)$ is the Planck function and $\epsilon_\lambda \in [0,1]$ is the **emissivity** (or **emittance**). In a stationary equilibrium case, the source function is equal to the energy absorbed by the body.

Emissivity is defined as the ratio of the emitted radiance and that of a blackbody (through the Planck function) at the same wavelength:

$$\epsilon_\lambda = \frac{W_\lambda}{B_\lambda(T)} = \frac{W_\lambda}{\sigma T^4}$$

Keep in mind that **the energy absorbed by a body depends on the energy of the incident radiation and on the body absorbance. The energy emitted depends on the emissivity (and so the material) of the body and its temperature.**

Emission

We consider a grey body, i.e. an opaque body (transmittance equals zero) that absorbs with the same efficacy at each wavelength, and a black body, in the form of infinite plates exchanging radiation only. Consider the plates in thermal equilibrium, i.e. plates absorb and emit the same amount of energy (this can be reached by introducing a medium between the plates).

The single plate balance will be

$$blackbody\text{:}\ \ \epsilon_g \sigma T^4 \alpha_b + \epsilon_b \sigma T^4 \rho_g \alpha_b = \epsilon_b \sigma T^4$$
$$greybody\text{:}\ \ \epsilon_b \sigma T^4 \alpha_g = \epsilon_g \sigma T^4$$

Considering that $\epsilon_b = \alpha_b = 1$ and resolving the equation system we get

$$\alpha_g \sigma T^4 + \rho_g \sigma T^4 = \sigma T^4$$
$$\alpha_g \sigma T^4 = \epsilon_g \sigma T^4$$

The first equation is an identity since $\alpha_g + \rho_g = 1$.

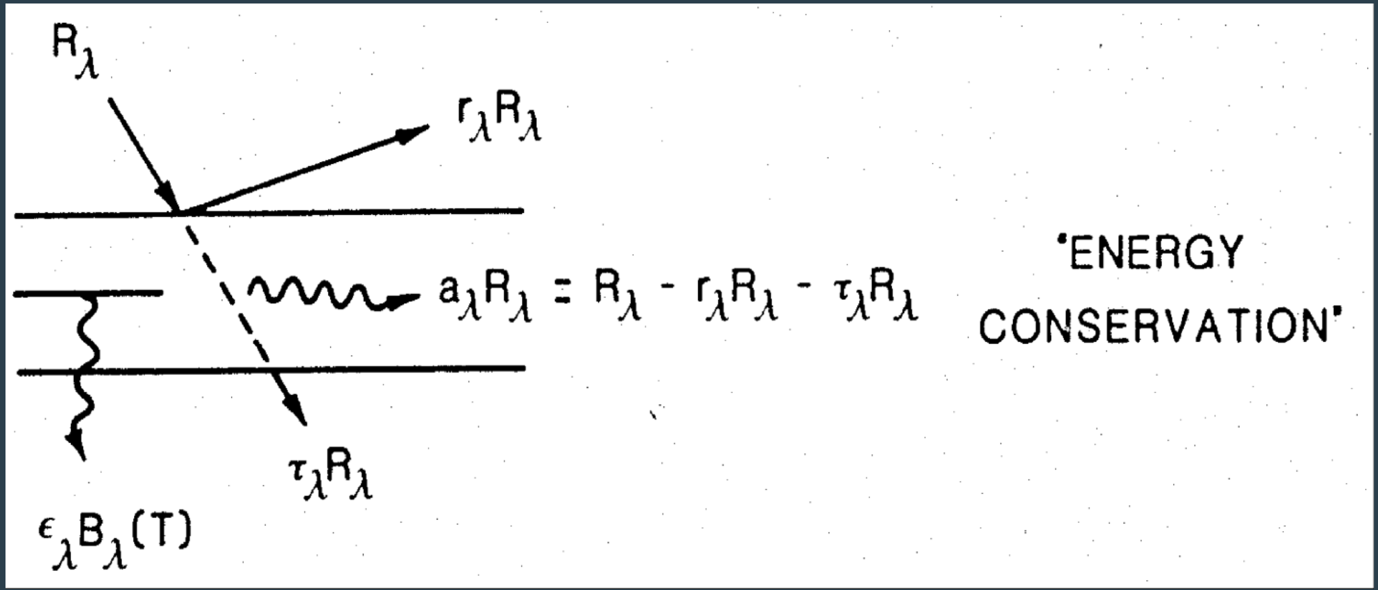
The second is the *Kirckhoff law* that can be generalized as: $\alpha = \epsilon$

Kirckhoff law holds also if we consider two opaque grey bodies

Radiation Balance

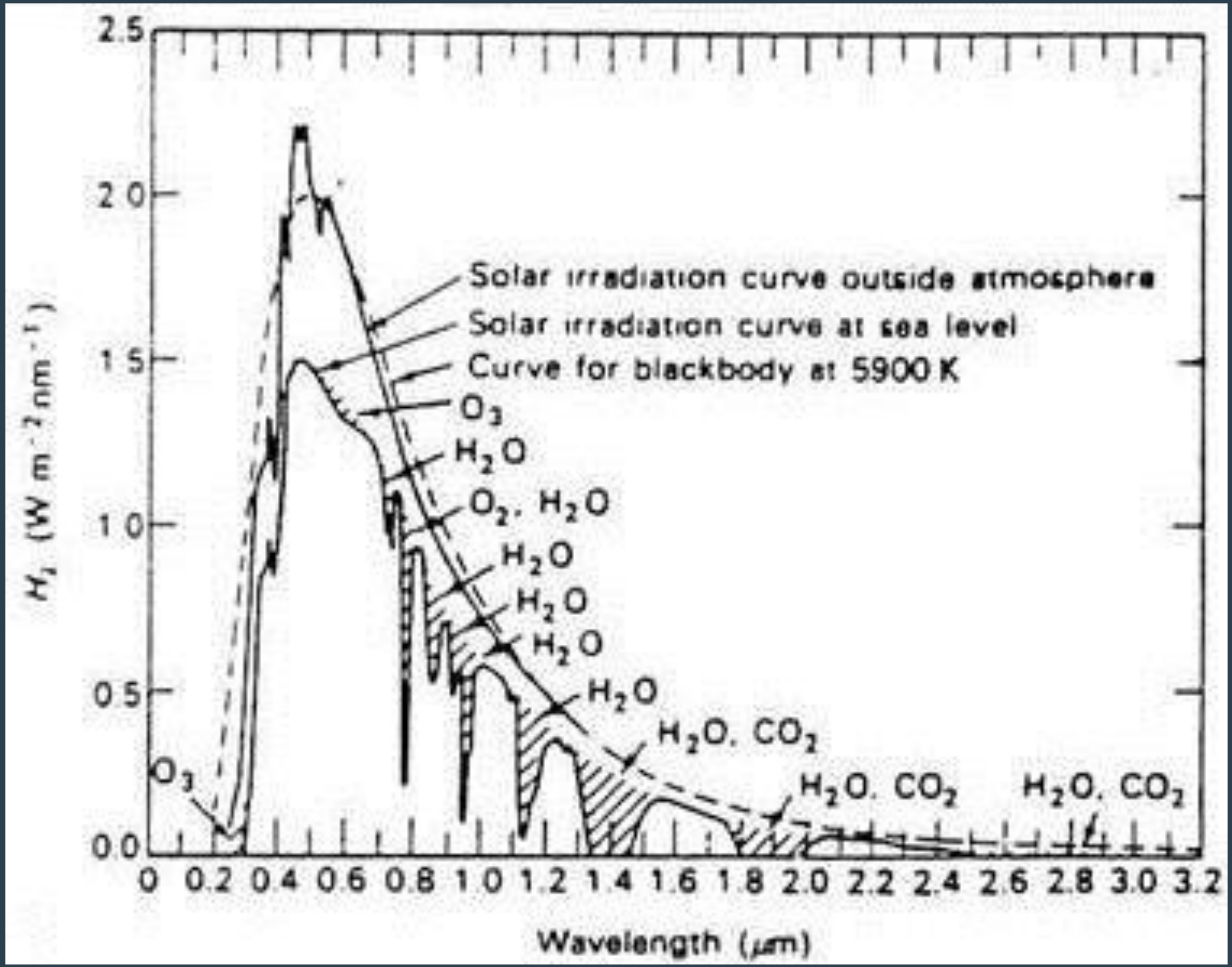
If α_λ, ρ_λ, and τ_λ represent the fractional absorption, reflectance, and transmittance, respectively, then conservation of energy says

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$



- A perfect mirror has $\rho_\lambda = 1$, and $\alpha_\lambda = \tau_\lambda = 0$.
- A black body has $\alpha_\lambda = 1$, and $\rho_\lambda = \tau_\lambda = 0$.
- An opaque body has $\tau_\lambda = 0$, so radiation is either absorbed or reflected $\alpha_\lambda + \rho_\lambda = 1$

Radiation extinction by the atmosphere



Solar radiation is extincted by the atmospheric gases, aerosols and clouds.

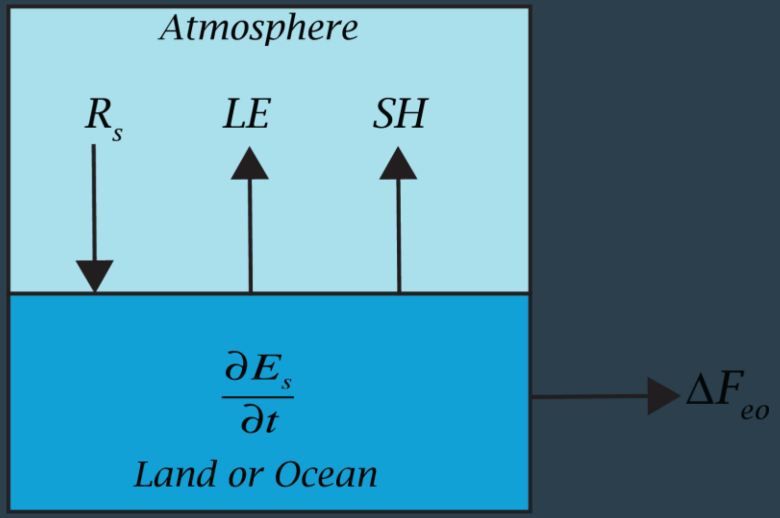
The transmitted portion of the solar radiation arrives at the Earth surface and it is mostly absorbed by the hydrosphere, lithosphere, cryosphere and biosphere, and in minimal part reflected.

Surface Energy Balance

The processes that determine energy transfer between the surface and atmosphere include solar and infrared radiative transfer, fluxes of energy associated with fluid motions of the atmosphere and ocean, and movement of energy through the soil.

In the most general form, the surface energy balance can be written as

$$\frac{\partial E_S}{\partial t} = R_S - LE - SH - \Delta F_{eo}$$



where $\partial E_S/\partial t$ is the storage of energy in the soil and water, R_S is the net radiative flux of energy at the surface, LE is the latent heat flux from the surface to the atmosphere, SH is the sensible heat flux from the surface to the atmosphere and ΔF_{eo} is the horizontal flux out of the column of land-ocean below the surface.

Heat Storage

Energy storage in the surface is very important for the seasonal cycle of temperature over the oceans and the diurnal cycle over land and ocean. The amount of energy in the surface may be written as the product of an effective heat capacity for the earth–ocean system $\bar{C}_{eo}$ and a corresponding mean temperature T_{eo}

$$E_S = \bar{C}_{eo} T_{eo}$$

The **heat capacity** (the amount of energy that is required to raise the temperature of the body by 1°C) is defined as the heat required to force a temperature variation

$$C = \frac{Q}{\Delta T} = \frac{m c_p \Delta T}{\Delta T} = m c_p$$

where c_p is the specific heat at constant pressure (the amount of energy that is required to raise the temperature of a unit mass of a body by 1°C keeping the pressure as constant).

Sensible and Latent Heat

Sensible heat flux SH is the transfer of heat between the surface and the atmosphere that does not imply a variation in the state of the involved particles.

$$SH = c_p \rho C_{DH} U_r (T_S - T_a(z_r))$$

Latent heat flux LE is the emission or absorption of heat by water particles during a phase change.

$$LE = L \rho C_{DE} U_r (q_S - q_a(z_r))$$

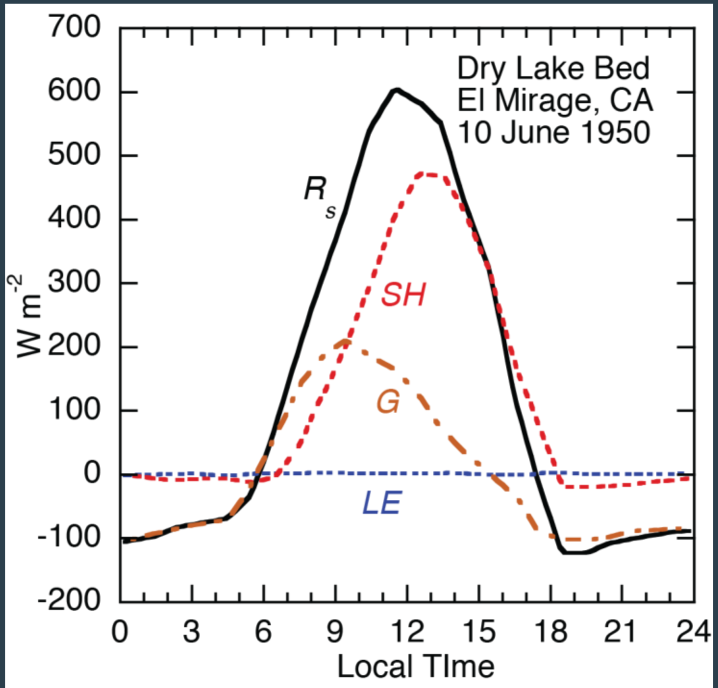
where ρ is the air density, c_p is the specific heat at constant pressure, L is the latent heat of vaporization and C_{DH} and C_{DE} are aerodynamic transfer coefficients for heat and moisture, respectively. Subscripts S and a indicate values for the surface and the air at the reference level, respectively.

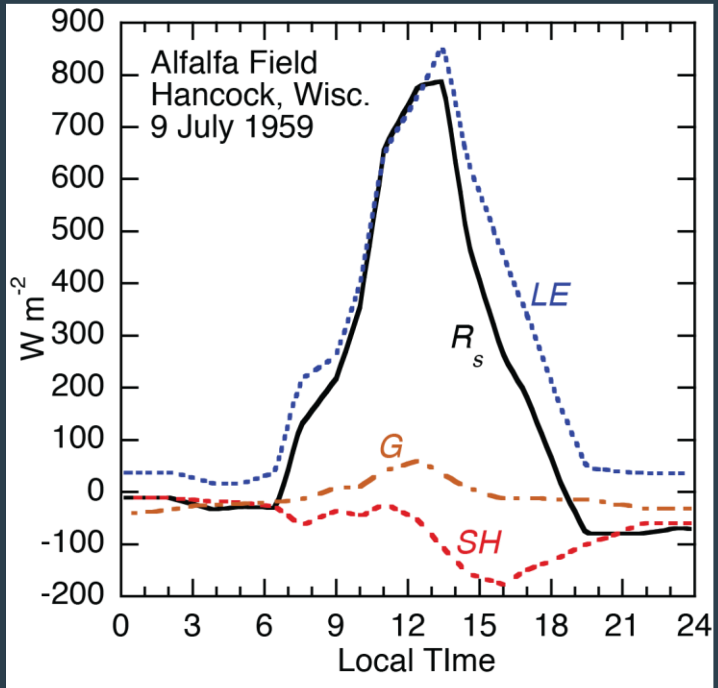
Evaporation is the change of state in a substance from a liquid to a gas.
For evaporation to take place, energy is required. The energy can come from any source: the sun, the atmosphere, the earth, or bodies on the earth such as humans.

Evaporation cools the fluid/surface the liquid evaporates from as it uses its heat to complete the phase change. Evaporation does not change the temperature of the evaporated particle but that of the fluid/surface the particle evaporates from.

Surface Energy Balance

$$G = \frac{\partial E_S}{\partial t}$$

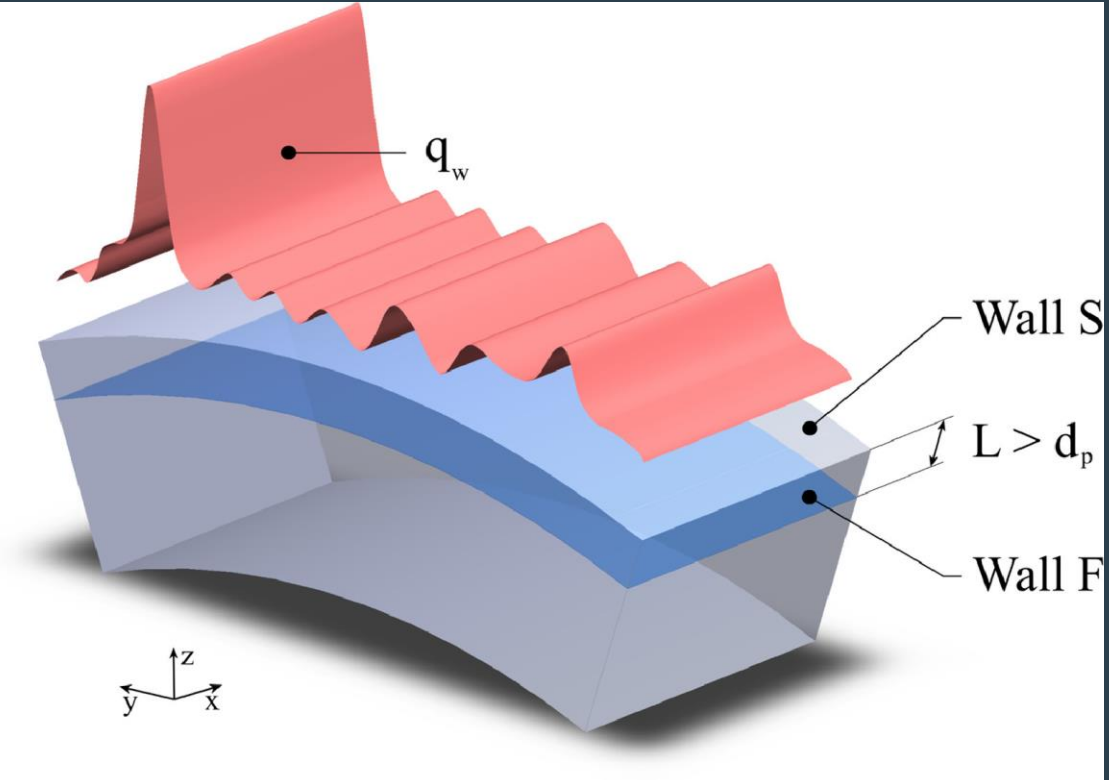




Heat Transfer

Once the surface temperature history has been accurately reconstructed,

- The surface heat flux can be evaluated by solving the heat conduction equation to solve the movement of heat into the surface
- The vertical heat flux can be evaluated to assess the thermal impact of the surface on the atmosphere

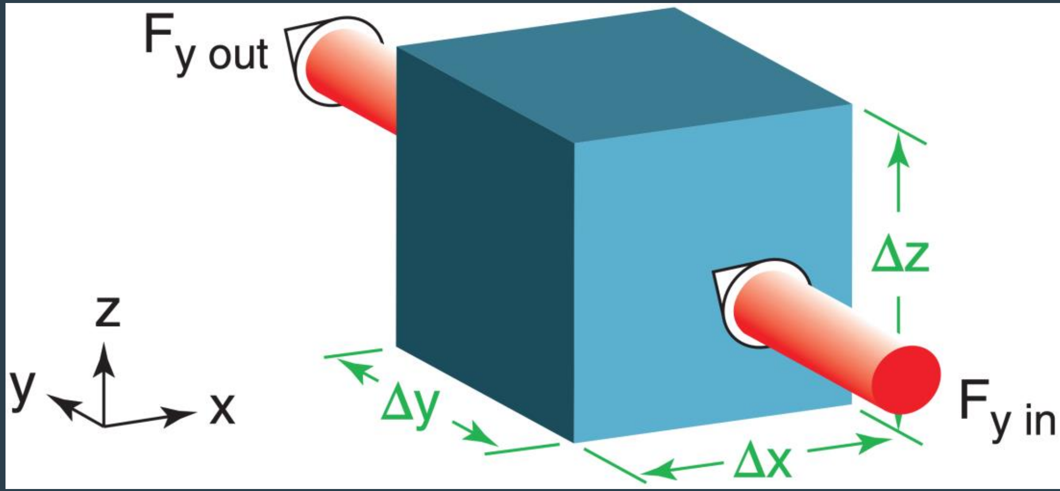


Heat Transfer

Thermal energy transferred (Δq) per unit mass causes temperature change: ΔT = Δq/Cp.

Dividing this equation by time interval Δt gives a forecast equation for temperature: ΔT/Δt = (1/Cp)·Δq/ Δt.

A heat flux F (J m–2 s–1, or W m–2) into the volume could increase the temperature, but a heat flux out the other side could decrease the temperature.



Thus, with both inflow and outflow of heat, net thermal energy will be transferred into the cube of air if the heat flux decreases with distance s across the cube: Δq/Δt = –(1/ρ)·ΔF/Δs. The inverse density factor appears because Δq is energy per unit mass.

Heat Transfer

Heat flux convergence such as this causes warming, while heat flux divergence causes cooling. This flux gradient (change with flux across a distance) could happen in any of the three Cartesian directions. Thus, the temperature forecast equation becomes:

$$\frac{\Delta \bar{T}}{\Delta t} = -\frac{1}{\rho c_p}\frac{\Delta F_{x_j}}{\Delta x_j} + \frac{1}{c_p}\frac{\Delta S}{\Delta t}$$

where, for example, ΔFy/Δy is the change in northward-moving flux Fy across a north-south distance Δy. Additional heat sources can occur inside the cube at rate ΔSo/Δt (J kg–1 s–1) such as when water vapor already inside the cube condenses into liquid and releases latent heat. The equation above is the Eulerian heat-budget equation, also sometimes called a heat conservation or heat balance equation.

Heat Transfer

For indoor air temperature measurements, heat transfer via convection at the boundary layer, and by radiation to or from the surroundings are prevailing. The measurement error at steady state conditions thus depends on reflective properties of the involved surfaces, the size and shape of the sensor and its position relative to the surrounding surfaces as well as the flow field surrounding it. For a temperature sensor immersed in air and being in thermal balance, the heat transfer due to radiation will be balanced by convective heat transfer so that:

$$q_{rad} = q_{conv}$$

where

$$q_{rad} = \epsilon A \sigma (T_{wall} - T_{sensor})$$

and

$$q_{conv} = A h_{conv} (T_{sens} - T_{air})$$

The convection heat transfer is dependent on the characteristics of the air flow field around the sensor, including flow direction and turbulence intensity.

Heat Transfer

$LE = \rho\lambda\overline{w'q'}$ Latent heat flux expressed through the turbulent flux of water vapor $\overline{w'q'}$, where ρ is the air density and the λ latent heat of vaporization

The temperature balance $\bar{T}$ for a wet surface can be simplified to

$$c_p \frac{\partial \bar{T}}{\partial t} = -\lambda \frac{\partial \overline{w'q'}}{\partial z}$$

with c_p the specific heat at constant pressure. Introducing the Bowen ratio $B = \frac{c_p}{\lambda}\frac{\overline{w'T\prime}}{\overline{w'q\prime}}$ we get

$$\frac{\partial \bar{T}}{\partial t} = -\frac{1}{B}\frac{\partial \overline{w'T'}}{\partial z}$$

Assuming a flux-gradient relation we get

$$\frac{\partial \bar{T}}{\partial t} = \frac{K_h}{B}\frac{\partial^2 T}{\partial z^2}$$

In the presence of a heat source q (with k the thermal conductivity), the balance becomes

$$\frac{\partial \bar{T}}{\partial t} = \frac{K_h}{B}\frac{\partial^2 T}{\partial z^2} + \frac{q}{k}$$

The Laboratory Experience

Scope

- Evaluate the temperature transition of a surface associated with heat exchange with the atmosphere, with and without a heating source (e.g., the sun).
- Evaluate the different temperature transitions of homogeneous dry, homogeneous wet and wet surfaces with impurities hit by the same heating.
- Quantify the impact of heat storage and evaporation.

Lab setup

Heat Source

Surface under examination

$M_{sponge} = 10$ g

$M_{wet\ sponge} = 50$ g

Dry sponge

$C_p = 1.28$ J/g°C

Wet sponge

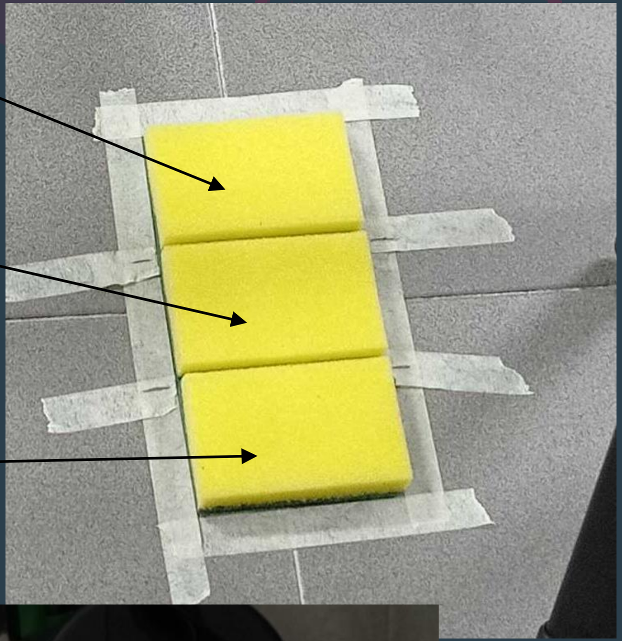
$C_p = 4.186$ J/g°C

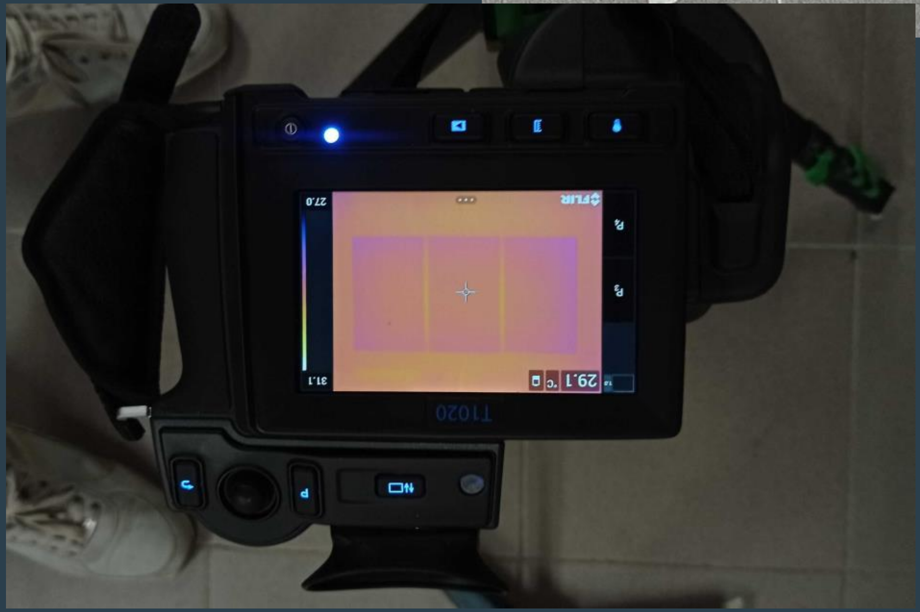
Wet-salty sponge

$C_s = 35$ g/Kg

$C_p = 3.901$ J/g°C

The Domain





The experience

The exercise will consist of four phases of constant monitoring to “force” the heat storage and evaporation effects of the sponge:

- Heat storage: evaluate the effect of warming and cooling of the sponges’ surface when evaporation is prevented
- Evaporation: evaluate the effect of warming and cooling of the sponges’ surface when evaporation is permitted (Latent heat of evaporation, $L_{wet\ sponge}$ = 2272 J/g, $L_{salty\ sponge}$ = 2360 J/g)

Research Questions

- What is the role of heat capacity in the surface temperature transitory?
- What is the role of evaporation on the surface temperature transitory?
- How do impurities impact the transitory?
- What is the heat exchanged with the atmosphere during the different phases?
- How do the surfaces exchange heat?
- Is there parallelism with an outdoor environment?

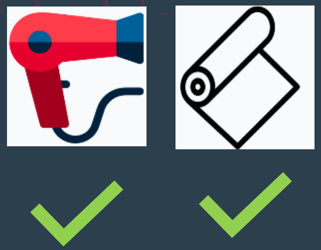
Supporting material

At the end of the experience, the group will be provided with:

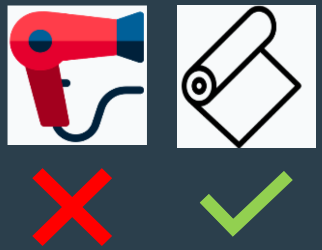
- The collected sequence of thermal images measured with the IR camera, both in .jpg and .mat
- A code in MATLAB to retrieve and save the surface temperature from the images in a text file
    - Tune the input/output
    - Manual identification of the pixel of temperature retrieval

Phases of the exercise

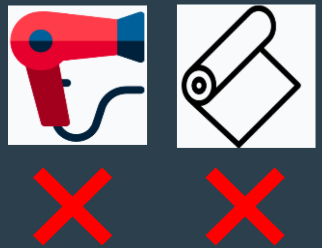
-Phase 1: Hairdryer turned **on with** film on the sponges
Main contribution: heat storage
Which sponge heats up first? Which more?



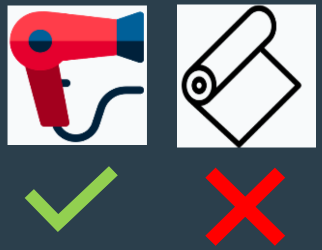
-Phase 2: Hairdryer turned **off with** film on the sponges
Main contribution: heat storage
What happens differently than in Phase 1?



-Phase 3: Hairdryer turned **off without** film on the sponges
Main contribution: evaporation
What is the contribution of evaporation?



-Phase 4: Hairdryer turned **on without** film on the sponges
Main contribution: heat storage & evaporation
What contribution dominates in each sponge?
Does the surface of the sponges heat evenly?



How to use the infrared camera

Settings

Before taking the photo (mandatory, unchangeable after):

- Adjust the focus of the camera
- Set the range of temperature (set by us)
- Determine the area of interest

Other settings adjustable after the image is acquired:

- Level and span
- Color table
- Object (Ambient) parameters

Focus

- An image with an incorrect focus is useless!
- To adjust the focus, point the camera on a surface with square geometry and large thermal contrast

A wooden table on a marble floor

Area of interest

- It defines the area we want to capture with the shot
- The subject of our investigation should be in the centre of the image
- The cameraman should be at a convenient distance from the object and a convenient angle to avoid self reflection

Level and Span

- The span is the range of the thermal scale (not the temperature range) on the screen (it is defined by the minimum and maximum temperature the camera is reading at each moment; it is based on what we look at).
- The level is the central value of the span (located in the photographic area).

Color table

- It defines how we are going to visualize the thermal image (remember the raw thermal image is in black and white)
- It helps detailing certain aspects depending on the choice of color table

Rule of Thumb: use high-contrast color table for images with low span, low-contrast color table for images with high span

Ambient parameters

- Parameters to be set to make our measurement realistic
- To change the parameters means to change the temperature

Setup the ambient parameters

- The ambient parameters are emissivity, reflective apparent temperature, air temperature, relative humidity and distance (plus transmittance compensation when a transmitting body is considered).
- Setting these parameters allow to compensate for the object radiative properties and the filter of the atmosphere

Operate in "apparent temperature" mode

- The apparent temperature is the temperature measured by the infrared camera if we assume that all the radiation comes from a black body near the camera
- To setup the camera for the apparent temperature mode, you must set the emissivity to 1 and the distance to 0 m
- The more the emissivity of a body approaches 1, the more the apparent temperature is the real temperature of the object