Thermal Radiation II

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I. Objectives

This experiment aims to provide insights into the radiation absorption properties of materials and validate theoretical principles using experimental data. The main objectives of this experiment are as follows: Measurement of absorptivity of different transparent materials to evaluate their interaction with thermal radiation. Verification of Beer's absorption law by analysing the relationship between the functional parameters.

II. Essential Background

Thermal radiation refers to the transfer of energy via electromagnetic waves, primarily in the infrared range. Unlike conduction and convection, which rely on a medium (solid, liquid, or gas), thermal radiation can occur in a vacuum. The main modes of heat transfer are as follows:

- **Conduction:** Heat transfer within solids caused by molecular interactions, driven by temperature gradients.
- **Convection:** Heat transfer through fluid motion (liquids or gases) driven by density changes due to temperature differences.
- **Thermal Radiation:** Transfer of energy through electromagnetic waves emitted by objects with temperatures above absolute zero, where the intensity depends on temperature and the material's emissive properties.

A. Diffuse and Gray Surfaces

1) Diffuse Surfaces:

- **Uniform Emission or Reflection:** Diffuse surfaces emit or reflect radiation equally in all directions, regardless of angle.
- **Isotropic Radiation:** Radiation from a diffuse surface is uniform in all directions.
- **Mathematical Representation:** For a diffuse surface, the radiation intensity I_e is constant. If $I_e = I_0$ at one angle, it remains constant in all directions.
- **Lambert's Cosine Law:** Radiation intensity decreases with angle θ from the surface normal, expressed as:

$$\boxed{I_e(\theta) = I_0 \cos(\theta).}$$

2) Gray Surfaces:

- **Constant Emissivity:** A gray surface has a constant emissivity ϵ across all wavelengths, unlike real surfaces where emissivity varies.
- **Emissive Power:** The total power radiated E by a gray surface is:

$$\boxed{E = \epsilon\sigma T^4},$$

  where:
  - σ is the Stefan-Boltzmann constant,
  - T is the surface's absolute temperature.
- **Simplification:** The gray surface model simplifies analysis by avoiding wavelength-dependent emissivity, although real surfaces often exhibit such dependence.
- **Comparison to Blackbody:** A blackbody has $\epsilon = 1$, while a gray surface has $\epsilon < 1$, meaning it emits less radiation at the same temperature.

B. Relationship Between Intensity and Emissive Power for Diffuse Surfaces

The emissive power E for a diffuse surface is derived by integrating the radiation intensity I_e over all emission angles:

$$\boxed{E = \int_0^{2\pi} \int_0^{\pi/2} I_e \cos(\theta) \sin(\theta) \, d\theta \, d\phi.}$$

Here, $\cos(\theta)$ accounts for the perpendicular component of radiation, as radiation emitted at angle θ spreads over a larger area.

For a diffuse surface, where I_e is constant, the integration simplifies to:

$$\boxed{E = \pi I_e.}$$

Thus, the emissive power E is proportional to the intensity I_e by a factor of π:

$$\boxed{E = \pi I_e.}$$

C. *Beer's Law of Absorption*

Beer's law explains how light or electromagnetic radiation is absorbed by a medium. The absorption depends on the medium's thickness and the light's initial intensity. The mathematical expression is:

$$\boxed{I = I_0 e^{-\alpha x}},$$

where:

- I = Intensity of light after passing through the material,
- I_0 = Initial intensity of the incoming light,
- α = Absorption coefficient (units: m^{-1}),
- x = Thickness of the medium (units: m).

III. Experimental Setup

The experimental setup is designed to study both thermal and light radiation phenomena using a combination of components. A metal plate equipped with a heater generates heat flux, while temperature monitoring is performed with filters of different transmittance levels to analyze light absorption. A radiometer measures radiation intensity, and the heater's power is electronically regulated for precise control. An electronic console manages the heating element and data acquisition, ensuring detailed analysis of radiation principles under variable conditions.

Fig. 1. Experimental Setup

IV. Experimental Procedure

- Assemble the Heat Radiation Module with the light source, power source, and other apparatus.
- Connect the experimental setup with SCADA software.
- Record initial temperature and radiation intensity values (lux) without any filters to establish a baseline. This is important as the radiation energy per unit area can be described by integrating the intensity over all wavelengths and solid angles:

$$\boxed{e = \int\int I(\lambda, \theta.\phi), d\lambda\, d\omega.}$$

  - e is the Total radiation energy per unit area
  - $I(\lambda, \theta.\phi)$ is theIntensity as a function of wavelength, polar angle, and azimuthal angle
- Set the power to 110 W using SCADA software.
- Insert filter 1 (emissivity = 0.3) into the radiation path at a position closest to the source and record the lux and temperature readings.
- Gradually move the filter further away from the source and record measurements at each position.
- As the filter moves away, observe an exponential decay as described by Beer's law:

$$\boxed{\tau = \frac{I_f}{I_{\max}} = e^{-Kx}}$$

$$\boxed{\alpha + \beta + \tau = 1}$$

  - τ is Transmittivity
  - α is Absorptivity
  - β isReflectivity
  - x is the Distance
- Replace the filter with filter 2 (emissivity = 0.6) and repeat the steps.
- Adjust the power source to form a 30-degree angle with the filter and measure the temperature and radiation intensity.
- Realign the source to a $-30°$ angle and repeat the measurements with both filters.
- Intensity reduction with angular displacement can be described using:

$$\boxed{I_2 = I_1 cos(\omega_2)}$$

  - I_1 is the Initial intensity
  - ω_2 is the Angle between the source and perpendicular distance
- Replace the filter with a plate of thickness = 1.2 mm and record the temperature and radiation intensity.

- Radiation passing through the plate is expected to follow the same exponential decay .

$$\boxed{\tau = e^{-Kx}}$$

($x = 1.2\,\mathrm{mm}$)

- Compare the results to the values obtained with the filters.
- Adjust the power level to 118 W and repeat the procedure.

V. Calculation and Results

This experiment aims to measure how much light is absorbed within a material (volume absorption, K) and at its surface (surface absorption, α). These measurements help us understand how different materials absorb light in certain conditions.

Note: We were unable to gather data for this experiment due to some constraints in setup, so we took the data from another Group.

For an inclination of $0°$ and a power of 118W, the max intensity was found to be 430 lux.

Intensity Readings for Filter 1 with $\alpha = 0.3$

Distance	Intensity
Pos 1	280
Pos 2	261
Pos 3	257

Intensity Readings for Filter 2 with $\alpha = 0.6$

Distance	Intensity
Pos 1	182
Pos 2	153
Pos 3	150

For an inclination of $0°$ and a power of 110W, the intensity was found to be 385 lux.

Intensity Readings for Filter 1 with $\alpha = 0.3$

Distance	Intensity
Pos 1	251
Pos 2	238
Pos 3	235

Intensity Readings for Filter 2 with $\alpha = 0.6$

Distance	Intensity
Pos 1	169
Pos 2	140
Pos 3	137

For an inclination of $-30°$ and a power of 118W, the intensity was found to be 417 lux.

Intensity Readings for Filter 1 with $\alpha = 0.3$

Intensity Readings for Filter 2 with $\alpha = 0.6$

Distance	Intensity
Pos 1	270
Pos 2	257
Pos 3	251

Distance	Intensity
Pos 1	179
Pos 2	153
Pos 3	146

For an inclination of $30°$ and a power of 118W, the intensity was found to be 323 lux.

Intensity Readings for Filter 1 with $\alpha = 0.3$

Distance	Intensity
Pos 1	218
Pos 2	208
Pos 3	202

Intensity Readings for Filter 2 with $\alpha = 0.6$

Distance	Intensity
Pos 1	153
Pos 2	130
Pos 3	124

A. Volume Absorption Coefficient

The volume absorption coefficient (K) tells us how much light a material absorbs for each unit of its thickness. According to Beer's Law, the amount of light that passes through a material transmittance, (τ), depends on its thickness (x), following this relationship.

$$\boxed{\tau = \frac{I_f}{I_{\text{max}}} = e^{-Kx}}$$

Where:

- I_f is the intensity of light after passing through the material.
- I_{max} is the initial maximum intensity of light.

From the above equation, we can write:

$$K = -\frac{\ln(\tau)}{x}$$

B. Surface Absorption

Surface absorption (α) is the amount of light that a material absorbs at its surface. The concept of energy conservation states that the total absorption (α), reflection (β), and transmittance (τ) of light through a material must always be equal to 1.

$$\boxed{\alpha + \beta + \tau = 1}$$

Since we are neglecting β,

$$\alpha = 1 - \tau$$

C. Calculation of Volume Absorption Coefficient and Surface Absorption

For surface absorption α for the filter with $\alpha = 0.3$ at $0°$ inclination and power of 118W.

- Maximum intensity, $I_{\max} = 430$ lux.
- Thickness of the plate, $x = 1.2$ mm.
- Intensity readings, I_f: 280, 261, 257.

D. Calculations

$$\tau = \frac{I_f}{I_{\max}}$$

For $I_f = 280$:

$$\tau = \frac{280}{430} = 0.651$$

$$K = -\frac{\ln(0.651)}{1.2 \times 10^{-3}} = 357.70\,\mathrm{m}^{-1}$$

$$\alpha = 1 - 0.651 = 0.349$$

For $I_f = 261$:

$$\tau = \frac{261}{430} = 0.607$$

$$K = -\frac{\ln(0.607)}{1.2 \times 10^{-3}} = 416.02\,\mathrm{m}^{-1}$$

$$\alpha = 1 - 0.607 = 0.393$$

For $I_f = 257$:

$$\tau = \frac{257}{430} = 0.598$$

$$K = -\frac{\ln(0.598)}{1.2 \times 10^{-3}} = 428.47\,\mathrm{m}^{-1}$$

$$\alpha = 1 - 0.598 = 0.407$$

Averaged Values

The average value for the volume absorption coefficient:

$$K_{\text{avg}} = \frac{357.70 + 416.02 + 428.47}{3} = \boxed{400.73\,\mathrm{m}^{-1}}$$

The average value for surface absorption:

$$\alpha_{\text{avg}} = \frac{0.349 + 0.393 + 0.407}{3} = \boxed{0.383}$$

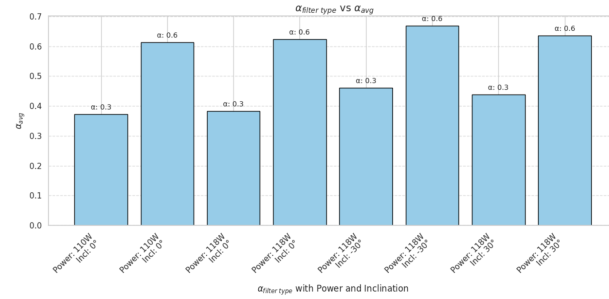

Fig. 2. $\alpha_{\text{filter type}}$ vs α_{avg}

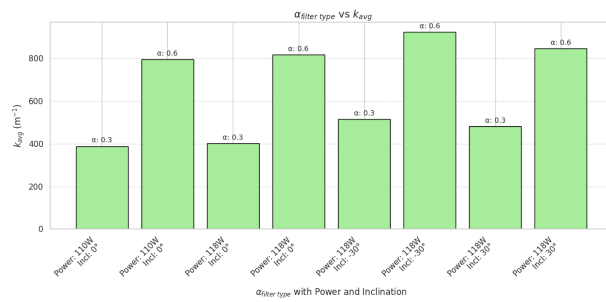

Fig. 3. $\alpha_{\text{filter type}}$ vs K_{avg}

TABLE I
FINAL VALUES TABLE

Inclination	**Power**	**α (filter type)**	**α_{avg}**	**K_{avg} (m^{-1})**
0°	110 W	0.3	0.3735	388.361
0°	110 W	0.6	0.6139	796.822
0°	118 W	0.3	0.383	400.73
0°	118 W	0.6	0.6241	818.485
−30°	118 W	0.3	0.4615	516.139
−30°	118 W	0.6	0.669	924.9
30°	118 W	0.3	0.4387	481.75
30°	118 W	0.6	0.636	846.426

FINAL VALUES TABLE

VI. ERRORS

1) **Error at $\pm 30°$ Angles:** The readings at $+30°$ and $-30°$ should ideally be the same due to the symmetrical setup. However, differences could have arisen from uneven lighting on either side of the experimental setup.
2) **Calibration Issues:** The temperature readings from the thermocouples may have been inaccurate due to calibration errors.
3) **Air Conditioning Influence:** Air currents caused by the air conditioning system might have disturbed the experiment, leading to unintended variations in measurements.
4) **Heat Loss:** Heat loss to the surroundings through convection could have impacted the accuracy of the results.
5) **Equipment Malfunction:** Some heat flux might not have been fully incident on the metal plates, resulting in errors in the recorded measurements.
6) **Human Errors:** Manual mistakes in recording data or adjusting experimental settings could have introduced

inconsistencies in the procedure.

VII. Conclusion

The experiment successfully measured how different transparent materials absorb light and confirmed Beer's law of absorption. By analyzing light passing through various filters at different angles and power levels, we calculated each filter's absorption properties, including the volume and surface absorption coefficients.

The results showed that materials with lower transparency had higher absorption, which matches theoretical expectations. This confirms that transparency is inversely related to absorption.

Moreover, the data aligned well with Beer's law, which states that light transmission decreases exponentially as it passes through absorbing materials. Any small differences between our results and theory were due to calibration issues, environmental factors, or human error.

VIII. References

1) F. Incropera and D. DeWitt, *Fundamentals of Heat and Mass Transfer*, 6th ed., Wiley, 2006.
2) Y. A. Cengel, *Heat and Mass Transfer: A Practical Approach*, 5th ed., McGraw-Hill, 2014.