Thermal Radiation

Abhinav Yadav
Mechanical Engineering
22110011
abhinav.yadav@iitgn.ac.in

Astitva Aryan
Mechanical Engineering
22110041
astitva.aryan@iitgn.ac.in

Dharavath Mahesh
Mechanical Engineering
22110073
dharavath.mahesh@iitgn.ac.in

Gamre Ketki
Mechanical Engineering
22110082
ketki.gamre@iitgn.ac.in

Mallepogula Charanteja
Mechanical Engineering
22110136
mallepogula.charanteja@iitgn.ac.in

Pasala Greeshma
Mechanical Engineering
22110182
greeshma.pasala@iitgn.ac.in

Shaury patel
Mechanical Engineering
22110241
shaurykumar.patel@iitgn.ac.in

Sridhar Thakur
Mechanical Engineering
22110257
sridharsingh.thakur@iitgn.ac.in

Harsh Chhapru
Mechanical Engineering
24120007
24120007@iitgn.ac.in

I. OBJECTIVES

The Objectives of the experiment are as follows :

- To apply the Stefan-Boltzmann law to calculate the rate of radiation heat transfer.
- To understand and measure thermal radiation from different surfaces.
- To analyze the impact of surface properties on emissivity and absorptivity.

II. ESSENTIAL BACKGROUND

A. What do you understand by thermal radiation ? How is Thermal Radiation Different from Conduction and Convection?

Thermal radiation is the emission of electromagnetic waves in all directions, primarily in the infrared spectrum, due to the thermal motion of particles within matter. It is a form of heat transfer that occurs through the emission of electromagnetic waves or photons. One of its key characteristics is that it does not require a medium to propagate, meaning it can take place in a vacuum.

Unlike conduction, which transfers heat through direct contact between molecules, or convection, which transfers heat through the bulk movement of fluids (liquids or gases), thermal radiation depends only on the temperature of the object and the properties of its surface. Conduction and convection require a medium for heat transfer, whereas radiation can occur in a vacuum.

B. Terminologies

(a) **Total and Monochromatic Emissive Power:**
  - **Total Emissive Power (E):** The total amount of thermal radiation energy emitted per unit area of a surface across all wavelengths per unit time.
  - **Monochromatic Emissive Power (E_λ):** The amount of thermal radiation energy emitted per unit area of a surface per unit time at a specific wavelength.

(b) **Total and Monochromatic Emissivity:**
  - **Total Emissivity (ε):** The ratio of the total emissive power of a surface to the total emissive power of a black body at the same temperature.
  - **Monochromatic Emissivity (ε_λ):** The ratio of the monochromatic emissive power of a surface to the monochromatic emissive power of a black body at the same wavelength and temperature.

(c) **Intensity of Radiation (I):** The power radiated per unit area per unit solid angle in a particular direction. It is used to describe the directional distribution of the emitted radiation.

(d) **Radiosity (J):** The total energy leaving a surface per unit area per unit time, including both the emitted radiation and the reflected radiation from other surfaces.

C. Rate of radiation heat transfer from a gray surface (at T_s) in an enclosed surrounding (at T_{sur}).

For a gray surface at temperature T_s, enclosed by surroundings at temperature T_{sur}, the net rate of radiation heat transfer is given by the following expression:

$$\boxed{q = \sigma \cdot \varepsilon \cdot A \cdot (T_s^4 - T_{\text{sur}}^4)}$$

Where:

- q = net rate of heat transfer (W)
- σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m$^2 \cdot$ K^4)
- ε = emissivity of the surface (dimensionless)
- A = area of the radiating surface (m²)
- T_s = surface temperature (K)
- T_{sur} = surrounding temperature (K)

D. *Beer's Law of absorption*

Beer's law (or Beer-Lambert law) states that the amount of radiation absorbed by a material is proportional to the intensity of the incident radiation and the absorbing properties of the material. Mathematically, it is expressed as:

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

Where:

- I = intensity of radiation after passing through a distance x in the material
- I_0 = initial intensity of radiation
- α = absorption coefficient of the material
- x = distance through the absorbing material (path length)

III. Experimental Setup

The experimental setup consists of the following components:

- **General Design:**
  - Bench-top unit with two sections: one for light radiation experiments, another for thermal radiation.
- **Main Components:**
  - **Metal Plate:** Fitted with a ceramic heating element on one side and a 150 W lamp (with diffuser) on the other.
  - **Heating Element:** Controlled by an electronic console (0-100% power regulation).
  - **Lamp:** 150 W with diffuser for controlled light radiation.
- **Light Radiation Accessories:**
  - **Luxmeter:** Measures light intensity (0 to 50,000 lux, with selectable light types: Day, Tungsten, Fluorescence, Mercury).
    - **Resolution:** 1 lux (0-1,999 lux), 10 lux (2,000-19,990 lux), 100 lux (20,000-50,000 lux).
  - **Filters:** Three Grey Neutral Density filters (A153, A152, A154).
- **Thermal Radiation Accessories:**
  - **Radiometer:** Measures radiation intensity (50 x 50 mm, 5µV/w/m²).
  - **Plane Surfaces:** Polished aluminum, anodized aluminum, brass, and two black bodies for studying radiation.
  - **Temperature Sensors:** Seven high-precision "T" type sensors.
- **Measurement and Control:**
  - **Power and Radiation Measurements:** Controlled and measured via the electronic console.
  - **Lux Measurement:** Performed using the luxmeter.

Fig. 1. Experimental Setup

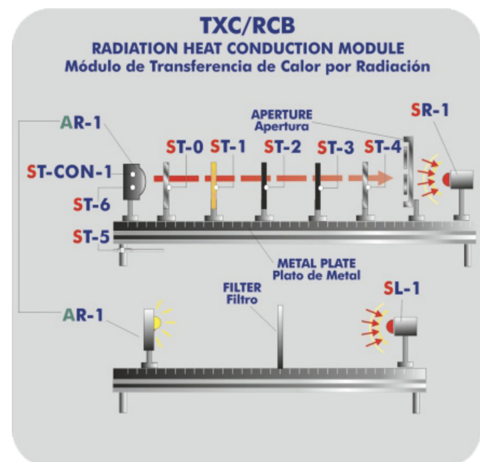

Fig. 2. Labelling of readings

IV. Procedure

1) First, set up the **Radiation Heat Conduction Module** by connecting it to the SCADA software. Then, calibrate all sensors:
   - **ST-3** - Black plate temperature (°C)
   - **ST-5** - White plate temperature (°C)
   - **ST-6** - Ambient temperature (°C)
   - **ST-7** - Radiator temperature (°C)
   - **SR-1** - Radiation intensity ($\frac{W}{m^2}$)
   - **SW-1** - Power delivered to the heating element (W)
2) Install the **black plate** in the setup and then turn on the module to start the experiment. Control the power delivered to the heating element using **SW-1** to adjust the intensity of heat applied to the black plate.
3) Record temperatures using **ST-3** for the black plate and **ST-7** for the radiator. Measure the radiation intensity with **SR-1**, and ensure all data is logged in real-time using the software.
4) Next, remove the black body surface and install the **white plate** and repeat the above procedure. Record the temperatures using **ST-5** for the white plate and **ST-7** for the radiator, while measuring radiation intensity using **SR-1**.
5) By varying the power input through **SW-1**, analyze

how it affects both the black and white body surface temperatures and radiation intensities. Apply the Stefan-Boltzmann Law:

$$E = \sigma\epsilon(T^4 - T_\infty^4)$$

Where,

- E - the radiation energy per unit area ($\frac{W}{m^2}$)
- σ - the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \frac{W}{m^2K^4}$)
- ϵ - the emissivity of the body surface
- T - surface temperature (K)
- T_∞ - room temperature (K)

6) For further calculations, record the readings using the software for **ST-3**, **ST-5**, **ST-7**, and **SR-1**. (Note: **ST-6** is almost constant as this experiment was conducted in a controlled environment.)
7) Finally, after the experiment is concluded, gradually reduce the heating element's power using **SW-1**. Allow the system to stabilize and cool down before shutting it off completely. Ensure that all experimental data is saved for further analysis.

V. Calculation and Results

A. *Calculating heat flux (ϵ)*

1. For Black Body Surface: The net heat transfer can be calculated using the following formula:

$$q = \epsilon\sigma\left(T_{\text{Plate}}^4 - T_{\text{Ambient}}^4\right)$$

Where:

- q is the net radiative heat transfer (W/m²)
- $\sigma = 5.67 \times 10^{-8}\,\text{W/m}^2\text{K}^4$ is the Stefan-Boltzmann constant
- ϵ is the emissivity of the surface (dimensionless)
- T_{Plate} is the plate temperature (in Kelvin)
- T_{Ambient} is the ambient temperature (in Kelvin)

For a black body, $\epsilon = 1$.

2. Given Readings for Black Surface: Using the following readings:

- Reading 1: $T = 45.2°\text{C}, T_{\text{Ambient}} = 28.9°\text{C}$
- Reading 2: $T = 42.8°\text{C}, T_{\text{Ambient}} = 29°\text{C}$
- Reading 3: $T = 39.3°\text{C}, T_{\text{Ambient}} = 29.6°\text{C}$

3. Calculations for Black Surface ($\epsilon = 1$): Convert temperatures to Kelvin:

$$T_1 = 45.2°\text{C} + 273.15 = 318.35\,\text{K}$$

$$T_{\text{Ambient},1} = 28.9°\text{C} + 273.15 = 302.05\,\text{K}$$

Similarly:

$$T_2 = 42.8°\text{C} = 315.95\,\text{K},\ T_{\text{Ambient},2} = 302.15\,\text{K}$$

$$T_3 = 39.3°\text{C} = 312.45\,\text{K},\ T_{\text{Ambient},3} = 302.75\,\text{K}$$

The theoretical heat flux for each case is:

$$q_{\text{theoretical}} = \sigma\left(T_{\text{Plate}}^4 - T_{\text{Ambient}}^4\right)$$

1. For Reading 1:

$$q_{\text{theoretical},1} = 5.67 \times 10^{-8}\left(318.35^4 - 302.05^4\right)$$

$$q_{\text{theoretical},1} = 5.67 \times 10^{-8}\left(1.028 \times 10^9 - 8.336 \times 10^8\right)$$

$$q_{\text{theoretical},1} = 5.67 \times 10^{-8} \times 1.945 \times 10^8 = \boxed{11.03}\ \text{W/m}^2$$

2. For Reading 2:

$$q_{\text{theoretical},2} = 5.67 \times 10^{-8}\left(315.95^4 - 302.15^4\right)$$

$$q_{\text{theoretical},2} = 5.67 \times 10^{-8} \times 1.654 \times 10^8 = \boxed{9.38}\ \text{W/m}^2$$

3. For Reading 3:

$$q_{\text{theoretical},3} = 5.67 \times 10^{-8}\left(312.45^4 - 302.75^4\right)$$

$$q_{\text{theoretical},3} = 5.67 \times 10^{-8} \times 1.175 \times 10^8 = \boxed{6.66}\ \text{W/m}^2$$

4. Practical Values for Black Surface:

- $q_{\text{practical},1} = 22.9\,\text{W/m}^2$
- $q_{\text{practical},2} = 20.9\,\text{W/m}^2$
- $q_{\text{practical},3} = 15.6\,\text{W/m}^2$

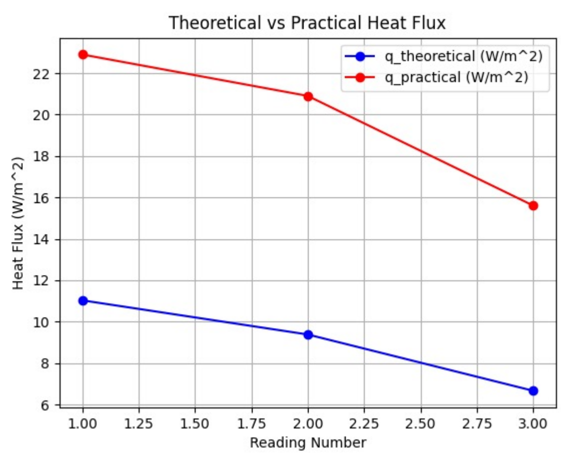

Fig. 3. Comparison of Theoretical and Experimental Heat fluxes

B. *Emissivity Calculation for Black Surface*

The formula for calculating emissivity (ϵ) is:

$$\epsilon = \frac{q}{\sigma\left(T_{\text{Plate}}^4 - T_{\text{Ambient}}^4\right)}$$

Where:

- $q_{\text{practical}}$ is the practical heat flux (in W/m²)
- $\sigma = 5.67 \times 10^{-8}\,\text{W/m}^2\text{K}^4$ is the Stefan-Boltzmann constant

1. Calculations for Each Reading

1. For Reading 1: Given:

- $T_{\text{Plate}} = 45.2°C = 318.35\,K$
- $T_{\text{Ambient}} = 28.9°C = 302.05\,K$
- $q_{\text{practical}} = 23.9\,W/m^2$

The emissivity is:

$$\epsilon = \frac{23.9}{5.67 \times 10^{-8}\,(318.35^4 - 302.05^4)}$$

$$\epsilon = \frac{23.9}{5.67 \times 10^{-8}\,(1023208121.76 - 829220633.22)}$$

$$\epsilon = \frac{23.9}{5.67 \times 10^{-8} \times 194536488.54}$$

$$\epsilon = \frac{23.9}{110.2895} \approx \boxed{0.216861}$$

2. For Reading 2: Given:

- $T_{\text{Plate}} = 42.8°C = 315.95\,K$
- $T_{\text{Ambient}} = 29.0°C = 302.15\,K$
- $q_{\text{practical}} = 20.9\,W/m^2$

$$\epsilon = \frac{20.9}{5.67 \times 10^{-8}\,(315.95^4 - 302.15^4)}$$

$$\epsilon = \frac{20.9}{5.67 \times 10^{-8}\,(996682952.83 - 831054768.35)}$$

$$\epsilon = \frac{20.9}{5.67 \times 10^{-8} \times 165628184.48}$$

$$\epsilon = \frac{20.9}{0093.8696} \approx \boxed{0.222667}$$

3. For Reading 3: Given:

- $T_{\text{Plate}} = 39.3°C = 312.45\,K$
- $T_{\text{Ambient}} = 29.6°C = 302.75\,K$
- $q_{\text{practical}} = 15.6\,W/m^2$

$$\epsilon = \frac{15.6}{5.67 \times 10^{-8}\,(312.45^4 - 302.75^4)}$$

$$\epsilon = \frac{15.6}{5.67 \times 10^{-8}\,(946015068.19 - 837296960.69)}$$

$$\epsilon = \frac{15.6}{5.67 \times 10^{-8} \times 108718107.5}$$

$$\epsilon = \frac{15.6}{0061.682} \approx \boxed{0.252968}$$

On taking average of all readings; i.e

$$\epsilon_{avg} = \frac{0.216861 + 0.222667 + 0.252968}{3} = \boxed{0.231415}$$

C. Emissivity Calculation for White Surface

1. Calculations for Each Reading

1. For Reading 1: Given:

- $T_{\text{Plate}} = 38.9°C = 312.05\,K$
- $T_{\text{Ambient}} = 30.4°C = 303.55\,K$
- $q_{\text{practical}} = 13.7\,W/m^2$

The emissivity is:

$$\epsilon = \frac{13.7}{5.67 \times 10^{-8}\,(312.05^4 - 303.55^4)}$$

$$\epsilon = \frac{13.7}{5.67 \times 10^{-8}\,(9481930061.91 - 8490259195.47)}$$

$$\epsilon = \frac{13.7}{5.67 \times 10^{-8} \times 8632900865.92}$$

$$\epsilon = \frac{13.7}{489.485} \approx \boxed{0.0279}$$

2. For Reading 2: Given:

- $T_{\text{Plate}} = 54.4°C = 327.55\,K$
- $T_{\text{Ambient}} = 30.5°C = 303.65\,K$
- $q_{\text{practical}} = 27.9\,W/m^2$

The emissivity is:

$$\epsilon = \frac{27.9}{5.67 \times 10^{-8}\,(327.55^4 - 303.65^4)}$$

$$\epsilon = \frac{27.9}{5.67 \times 10^{-8}\,(11510930057.44 - 8501452680.03)}$$

$$\epsilon = \frac{27.9}{5.67 \times 10^{-8} \times 3009477377.41}$$

$$\epsilon = \frac{27.9}{170.637} \approx \boxed{0.16350}$$

On taking average of all readings; i.e

$$\epsilon_{avg} = \frac{0.0279 + 0.16350}{2} = \boxed{0.0957}$$

Note: We were unable to gather more data due to issues with the experimental setup and time constraints. As a result, emissivity calculations were performed for only two surfaces with fewer readings.

VI. Errors

Reading	Theoretical Value $q_{\text{theoretical}}$ (W/m^2)	Practical Value $q_{\text{practical}}$ (W/m^2)	Error (%)
1	11.03	22.9	$\frac{22.9-11.03}{22.9} \times 100 = 51.83\%$
2	9.38	20.9	$\frac{20.9-9.38}{20.9} \times 100 = 55.12\%$
3	6.66	15.6	$\frac{15.6-6.66}{15.6} \times 100 = 57.31\%$

TABLE I
COMPARISON OF THEORETICAL AND PRACTICAL VALUES WITH ERROR

Surface	Measured Emissivity	Actual Emissivity	Error (%)
Black	0.231415	1	$\frac{1-0.231415}{1} \times 100 = 76.86\%$
White	0.0957	0	$\frac{0.0957-0}{0.0957} \times 100 = 100\%$

TABLE II
COMPARISON OF MEASURED AND ACTUAL EMISSIVITY VALUES WITH ERROR

- **Steady State Not Achieved:** The system did not reach a steady state during the experiment, which could result in fluctuating measurements and inconsistent data.
- **Non-Uniform Flux:** The heat flux was not uniform across the different plates, leading to variations in the recorded values.
- **Formula Limitations:** The formula used in the experiment is applicable only under specific environmental conditions. If the surroundings were not ideal, the results may not be accurate.
- **Non-Uniform Temperature:** The temperature was not consistent throughout the experiment, leading to uneven effects on different plates, which can alter the accuracy of the measured values.
- **Instruments at Different Temperatures:** Different instruments used in the experiment were at different temperatures, affecting their performance and contributing to errors in the recorded data.
- **Inconsistent Plate Temperatures:** Plates may have experienced different temperatures due to heat transfer, affecting the outcomes since temperature differences can lead to material expansion or other physical changes.
- **Misalignment of Plates:** Incorrect alignment of the plates could introduce mechanical errors, especially if precise positioning is required for accurate measurements.
- **Human Error:** Errors in handling the plates, reading instruments, or recording data could have led to inconsistencies in the experimental results.
- **Calibration Issues:** The instruments may not have been properly calibrated, leading to systematic errors in the measurements.
- **Environmental Variations:** Variations in the surrounding environment, such as airflow or humidity, could have influenced the results, especially if these factors affect the parameters being measured.

VII. Conclusion

The Radiation Heat Conduction experiment demonstrated that surface emissivity plays a critical role in heat transfer. The black plate, with higher emissivity, absorbed more heat and emitted more radiation compared to the white plate, which reflected more heat due to its lower emissivity. As power input increased, the surface temperatures and radiation intensity of both plates rose, confirming the Stefan-Boltzmann Law, which states that radiation emitted is proportional to the fourth power of the surface temperature. These findings highlight the importance of material properties in controlling thermal behaviour.

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.