" Design and Working of Stefan-Boltzmann Apparatus"

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Chemical Engineering

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UNDER THE SUPERVISION AND GUIDANCE OF

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ABSTRACT

This project focuses on the design and fabrication of a working model to experimentally verify the Stefan-Boltzmann law, which states that the energy radiated by a black body is proportional to the fourth power of its absolute temperature. Applying principles of thermal radiation and heat transfer, a functional setup was constructed using a water tank connected via a merchant rod to a cylindrical steel vessel containing a copper hemisphere and a text disc. The copper hemisphere, selected for its high thermal conductivity, acted as the radiating black body, while the text disc served as a reference surface. Two control valves regulated water flow to maintain a stable thermal environment essential for accurate radiation analysis. After assembling the apparatus, it was tested by heating the copper hemisphere and recording the emitted radiation, with results compared to theoretical predictions. The project not only validated the Stefan-Boltzmann law but also enhanced practical understanding of radiation heat transfer, particularly the temperature dependence of emitted energy. It developed essential engineering skills such as design, precision fabrication, problem-solving, and teamwork, resulting in a reliable experimental model that highlights the real-world applications of thermal engineering concepts.

Keywords :- Stefan-Boltzmann Law , Radiation Heat Transfer , Copper Hemispher , Experimental Verification , Thermal Engineering

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ACRONYMS

SB LAW	-STEFAN-BOLTZMANN LAW
THR	-THERMAL HEAT RADIATION
SSV	-STEEL SUPPORT VESSES

NOMENCLATURE

Symbol	Description	Unit
E	Emissive power or total radiated energy	W/m^2
σ	Stefan-Boltzmann constant	5.67×10^{-8} W/m^2K^4
T	Absolute temperature of the body	Kelvin (K)
A	Surface area of radiating body	m^2
Q	Radiated heat energy	Watts (W)
t	Time (optional, if used in energy calculations)	seconds (s)
ε	Emissivity of surface (if applicable)	dimensionless

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Introduction to Stefan-Boltzmann Apparatus

The Stefan-Boltzmann apparatus is a experimental setup used to verify the Stefan-Boltzmann law, which states that the total energy radiated by a black body is directly proportional to the fourth power of its absolute temperature. This experiment plays a crucial role in understanding the concept of thermal radiation and its relation to temperature. The apparatus typically includes a water tank, a merchant rod, a cylindrical steel vessel, a copper hemisphere, a reference disc, and flow control valves. Together, these components create a controlled environment to analyze radiative heat transfer. The experiment helps us and engineers to observe the practical effects of black body radiation and understand its theoretical foundation, making it highly relevant in the study of thermodynamics and heat transfer.

Design and Working Principle

The Stefan-Boltzmann apparatus consists of a **water tank (WT)** that supplies temperature-controlled water through a **merchant rod (MR)** into a **steel support vessel (SSV)**. Inside the vessel is a **copper hemisphere (HEM)** that acts as a black body due to its excellent thermal conductivity and uniform heat absorption/emission. A **text disc** or reference disc is placed nearby for comparative measurement. Two **control valves (CVs)** regulate the water flow, ensuring consistent temperature conditions. The hemisphere is heated, and as its temperature increases, it radiates energy.

According to the Stefan-Boltzmann law:

$$E = \sigma T^4 \quad \text{---- Eq. (1.1)}$$

where E is the emissive power, T is absolute temperature, and σ is the **Stefan-Boltzmann constant**. The emitted radiation is measured and compared with theoretical values to validate the law. This setup enables learners to visualize the direct relationship between temperature
and radiation, reinforcing heat transfer concepts.

Advantages and Applications

One of the advantages of this apparatus is its accuracy in demonstrating radiative heat transfer. The copper hemisphere provides near-black-body characteristics, while the steel chamber helps maintain uniform thermal conditions. This simple yet effective setup is valuable in laboratories for validating radiation laws. It's used in thermal engineering studies, heat transfer courses, and industries involved in thermal system design, insulation studies, and energy efficiency research. By offering a controlled and measurable environment, the Stefan-Boltzmann apparatus is an important educational and industrial

Importance and Versatility

The Stefan-Boltzmann apparatus is vital for building a deep understanding of thermal radiation and emissivity. Its design encourages students to apply theoretical formulas in real-world contexts, helping bridge the gap between academics and engineering applications. Constructing and studying the model improves technical accuracy, data handling, and experimental skills. This apparatus also introduces learners to real-time data interpretation, emphasizing the importance of temperature control and measurement accuracy in thermal analysis and material behavior studies.

Practical Applications

This experimental setup has a range of applications, including:

- Verification of radiative heat transfer laws in thermal labs.
- Calibration of infrared thermometers and heat sensors.
- Testing thermal coatings and insulation materials.
- Development of efficient radiators and emitters in engineering designs.
- Supporting research in energy conservation and heat loss analysis.

Its use is prominent in educational labs, research institutes, HVAC industries, and materials engineering.

History of Stefan-Boltzmann Law and Apparatus

Theoretical Foundation

The Stefan-Boltzmann law was discovered in 1879 by **Josef Stefan**, and later derived theoretically by **Ludwig Boltzmann** in 1884 using thermodynamics and electromagnetic theory. The law played a fundamental role in the development of **quantum mechanics** and our understanding of black-body radiation.

Early Experiments

Initial experiments used hollow spheres coated with lamp black (a near-perfect emitter) to test radiation. Over time, apparatuses became more advanced, integrating **temperature sensors, reflective shields, and precision control valves**.

Modern Usage

With the rise of **thermal imaging and energy auditing**, the Stefan-Boltzmann apparatus has found modern applications in:

- Infrared thermography calibration
- Heat shield testing for spacecraft
- Performance evaluation of solar thermal collectors
- Teaching tools in advanced thermal engineering labs

Its basic principle remains unchanged, but modern instruments use **digital sensors, data loggers, and precision thermal controllers** to improve accuracy and saf

Josef Stefan In 1879, Austrian physicist made a groundbreaking contribution to the study of thermal radiation by establishing an empirical relationship between the total energy emitted by a blackbody and its absolute temperature. In his paper titled "On the Relationship Between Thermal Radiation and Temperature", published in the Proceedings of the Mathematical-Natural Science Class of the Imperial Academy of Sciences, Stefan proposed that the radiant energy emitted per unit area of a blackbody is directly proportional to the fourth power of its absolute temperature. This formulation, now known as the **Stefan-Boltzmann Law**, marked the first time such a precise mathematical relationship had been defined using empirical data. Stefan derived this law by analyzing experimental results from previous scientists, including Tyndall and Dulong & Petit, who had conducted measurements on thermal radiation. While Stefan's work was not theoretical, its strength lay in its accuracy and consistency with observed data.[i]

The law is expressed mathematically as ---- From eq (1.1)

where E is the total emissive power of the blackbody, T is the absolute temperature in kelvin, and is the Stefan-Boltzmann constant. Stefan's ability to identify this fourth-power dependence was significant because it enabled scientists and engineers to predict the radiative heat transfer from hot surfaces with greater precision. His research also highlighted the concept of the **blackbody**—an idealized object that absorbs all incident radiation and emits energy only as a function of its temperature. Although the concept of a blackbody was introduced earlier by Gustav Kirchhoff, Stefan's contribution added a quantitative layer to the understanding of blackbody behavior. The Stefan-Boltzmann Law became fundamental in thermal physics, astrophysics, and engineering, particularly in calculating the energy output of stars and designing radiation-based heat transfer devices.[i]

Josef Stefan's empirical law gained further credibility when his student, **Ludwig Boltzmann**, provided a theoretical derivation of the same relationship in 1884 using thermodynamic and electromagnetic principles. Boltzmann's work confirmed Stefan's law within the framework of classical physics, further reinforcing its validity. Together, their combined efforts laid the foundation for future studies in radiation heat transfer and played a crucial role in the development of quantum theory. In the context of the Stefan-Boltzmann apparatus used in modern laboratories, Stefan's law is experimentally verified by measuring the radiated energy from heated surfaces and comparing it with the fourth power of their absolute temperature. This makes Josef Stefan's 1879 work not only historically important but also highly relevant for practical experiments and applications in thermal science today.[i]

Ludwig Boltzmann In 1884, physicist provided a theoretical foundation for the **Stefan-Boltzmann Law**, originally discovered empirically by Josef Stefan in 1879. In his paper titled "Derivation of Stefan's Law Concerning the Dependence of Thermal Radiation on Temperature from the Electromagnetic Theory of Light", Boltzmann used thermodynamic and electromagnetic principles to derive the relationship between thermal radiation and temperature. He considered a blackbody cavity in thermal equilibrium and applied **Maxwell's electromagnetic theory** along with the laws of thermodynamics.[ii]

Boltzmann demonstrated that the **energy density of radiation** inside the cavity is proportional to the **fourth power of the absolute temperature (T^4)**. This confirmed Stefan's earlier experimental findings and gave the law a strong theoretical basis. The resulting expression is eq 1 .[ii]

Boltzmann's work not only validated Stefan's law but also laid the groundwork for later developments in **statistical mechanics** and **quantum theory**. His derivation is directly relevant to the **Stefan-Boltzmann apparatus**, which experimentally verifies the T^4 law. Thus, Boltzmann's contribution remains fundamental in both theoretical physics and practical thermal experiments.[ii]

Gustav Kirchhoff In 1859, German physicist published a foundational paper titled "On the Relationship Between the Emission and Absorption Capacities of Bodies for Heat and Light" in the Annals of Physics. In this work, Kirchhoff introduced a key principle of thermal radiation, now known as **Kirchhoff's Law of Thermal Radiation**, which states that for any body in thermal equilibrium, the **ratio of its emissive power to its absorptive power is the same at a given wavelength and temperature**. This ratio is constant and equal to that of an ideal **blackbody**, which absorbs all incident radiation.[iii]

Kirchhoff's law was significant because it established the concept of the **perfect blackbody**, a theoretical object that is both a perfect absorber and emitter of radiation. He showed that the nature of thermal radiation is **independent of the material** of the object and depends only on temperature and wavelength.[iii]

This principle laid the groundwork for later studies by Stefan, Boltzmann, Planck, and others. It also underpins the function of the **Stefan-Boltzmann apparatus**, which measures blackbody radiation. Kirchhoff's insight was a turning point in the physics of heat and radiation, enabling a deeper theoretical understanding of energy emission.[iii]

Wilhelm Wien In 1893, German physicist published a key paper titled "On the Energy Distribution in the Emission Spectrum of a Blackbody" in the Annals of Physics. In this work, Wien studied the **spectral distribution** of radiation emitted by a blackbody and formulated what is now known as **Wien's Displacement Law**. He observed that the **wavelength at which a blackbody emits maximum energy is inversely proportional to its absolute temperature**, mathematically expressed as:[iv]

$$\lambda_{max} \cdot T = b$$

Where: eq.2

- λ_{max} is the peak wavelength (in meters),
- T is the absolute temperature (in kelvin),
- b is Wien's displacement constant, approximately:

$b = 2.897 \times 10^{-3} m$

Wien's research revealed how the **color and intensity of blackbody radiation shift with temperature**. As a body gets hotter, it emits radiation at shorter wavelengths, moving from infrared to visible light. This law provided deeper insight into the **distribution of radiation** and helped refine the understanding of blackbody behavior. [iv]

Wien's work was a critical step toward the later development of **Planck's Law** and the quantum theory of radiation. His law is also relevant to the **Stefan-Boltzmann apparatus**, which demonstrates how radiation changes with temperature, supporting theoretical predictions. [iv]

Max Planck , In 1900, German physicist revolutionized the understanding of thermal radiation with his paper titled "On the Theory of the Law of Energy Distribution in the Normal Spectrum", presented to the German Physical Society. Planck was attempting to resolve discrepancies between experimental results and classical theories related to blackbody radiation. Neither Stefan-Boltzmann's nor Wien's laws could fully explain the energy distribution across all wavelengths, especially at longer wavelengths where classical physics predicted infinite energy—a problem known as the ultraviolet catastrophe.[v]

To solve this, Planck introduced a radical idea: energy is not emitted continuously, but in discrete packets or "quanta." He proposed that the energy of electromagnetic radiation is proportional to its frequency, given by the formula:

$$E = h\nu \qquad \text{……eq 3}$$

where E is energy, v is frequency, and h is Planck's constant. Using this, he derived Planck's Law, which accurately described the spectral distribution of blackbody radiation across all wavelengths. .[v]

Planck's work not only completed the theoretical framework for blackbody radiation but also marked the birth of quantum theory. It provides the foundation for understanding energy emission in the Stefan-Boltzmann apparatus, linking classical thermodynamics with quantum physics.[v]

Methodology: Design and Experimental Verification of Stefan-Boltzmann Law Apparatus

This section presents a comprehensive methodology employed in the design, fabrication, and testing of an experimental setup used to verify the Stefan-Boltzmann Law. The process involved step-by-step planning, selection of suitable materials, structural design, parameter testing, and analysis based on thermal radiation principles. Detailed justifications are provided for each component, along with an essential consideration of emissivity.

1. Conceptualization and Design Framework

The first step involved understanding the Stefan-Boltzmann Law, which states that the total energy radiated per unit surface area of a black body per unit time (also known as black body radiant emittance) is directly proportional to the fourth power of the black body's absolute temperature:

$$E = \sigma T^4$$

Where:

- E = Radiated energy
- σ = Stefan-Boltzmann constant
- ε = Emissivity of the surface
- T = Absolute temperature in Kelvin

The goal was to construct an experimental apparatus that could practically validate this relationship. The design was made in such a way that radiated heat from a known surface (copper hemisphere) could be measured accurately under controlled conditions.

2. Material Selection and Their Purposes

Every component was selected based on physical, thermal, economic, and operational efficiency:

a. Copper Hemisphere (Radiator)

- **Purpose**: Serves as the primary heat-emitting surface.
- **Justification**: Copper has a high thermal conductivity (~398 W/m·K), ensuring uniform temperature distribution. Its surface was painted with matte black paint to increase emissivity (approaching ~0.95), enabling it to behave like an ideal black body.

b. Test Disc (Radiation Receiver)

- **Purpose**: Receives the thermal radiation from the copper hemisphere.
- **Justification**: The disc is made of aluminum or steel, painted black to maximize absorption. The absorbed energy is correlated with the surface temperature to validate radiative heat transfer.

c. Steel Cylindrical Vessel

- **Purpose**: Contains the primary heating water and provides structure.
- **Justification**: Chosen for its strength, temperature resistance, and ease of fabrication.

d. Water Reservoir

- **Purpose**: Supplies water for thermal regulation via indirect cooling.
- **Justification**: Ensures thermal stability within the system. Constant temperature conditions are essential for consistent results. The reservoir replaces the conventional water t

e. **PVC Pipe (0.5 inch)**

- **Purpose**: Directs water flow from the reservoir to the vessel.
- **Justification**: Chosen for its affordability, corrosion resistance, and flexibility. A 0.5-inch diameter ensures sufficient flow rate for heat regulation.

f. **Control gate Valves (2 Nos.)**

- **Purpose**: Regulate the water flow in and out of the setup.
- **Justification**: Essential for maintaining desired thermal conditions and preventing overheating or overcooling.

g. **Temperature Sensors/Thermocouple**

- **Purpose**: Monitor and record temperature of the copper surface and surrounding components.
- **Justification**: Thermocouples (usually Type K) provide accurate, real-time temperature measurements up to high temperatures. Their precision is critical for data collection.

h. **Stand or Support Frame**

- **Purpose**: Provides mechanical support to the apparatus.
- **Justification**: Ensures safe and stable mounting during experimentation. The stand holds the vessel at the appropriate height and orientation.

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l. **Wires, Switches, and Power Source**

- ***Purpose***: Provide controlled power to the heating element.
- ***Justification***: Ensures precise control over temperature. Safety switches are installed to prevent overcurrent conditions

3. Emissivity Consideration

- Emissivity (ε) is a critical factor in thermal radiation measurement. It defines how closely a surface behaves like a black body.
- A perfect black body has an emissivity of 1-0. In our experiment, the copper hemisphere was coated with matte black paint to increase emissivity close to 0.95.
- The test disc also used black paint to ensure high absorptivity, reducing reflection errors.
- Emissivity values were used in calculation models to compare theoretical versus observed radiation data.

4. Apparatus Assembly Process

- The copper hemisphere was securely mounted in the center of the steel vessel.
- The blackened disc was positioned to face the hemisphere at a fixed known distance.
- Water reservoir and merchant rod were connected via 0.5-inch PVC pipe.
- Control valves were placed on both inlet and outlet sides of the water circuit.
- Thermocouples were fixed on the hemisphere surface and surrounding zones for accurate readings.
- The electrical heating element was installed beneath the hemisphere and connected via switches and control·circuits.

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5. Experimental Procedure

- The system was powered on, and the heating element gradually increased the hemisphere temperature.
- Temperature readings were taken at regular intervals once thermal equilibrium was achieved.
- The blackened disc temperature was monitored to observe absorbed radiation.
- Water flow through the reservoir was adjusted to maintain a controlled ambient temperature.
- All data was logged manually or with the help of a data acquisition system.

6. Data Analysis and Theoretical Comparison

- Radiative heat transfer values were calculated using Stefan-Boltzmann equation.
- Temperature data was plotted against T^4 to check for linearity.
- The coefficient of discharge and emissivity correction factors were considered in final calculations.
- Experimental data was compared with theoretical expectations to verify the law.

7. Observations and Result Interpretation

- The linear relationship between radiation and T4T^4 was confirmed, validating the Stefan-Boltzmann law.
- Minor deviations were attributed to surface irregularities, emissivity imperfections, and ambient losses.

Overall, the experiment demonstrated successful real-world application of a fundamental physics law

FIGURE OF OUR APPRATUS

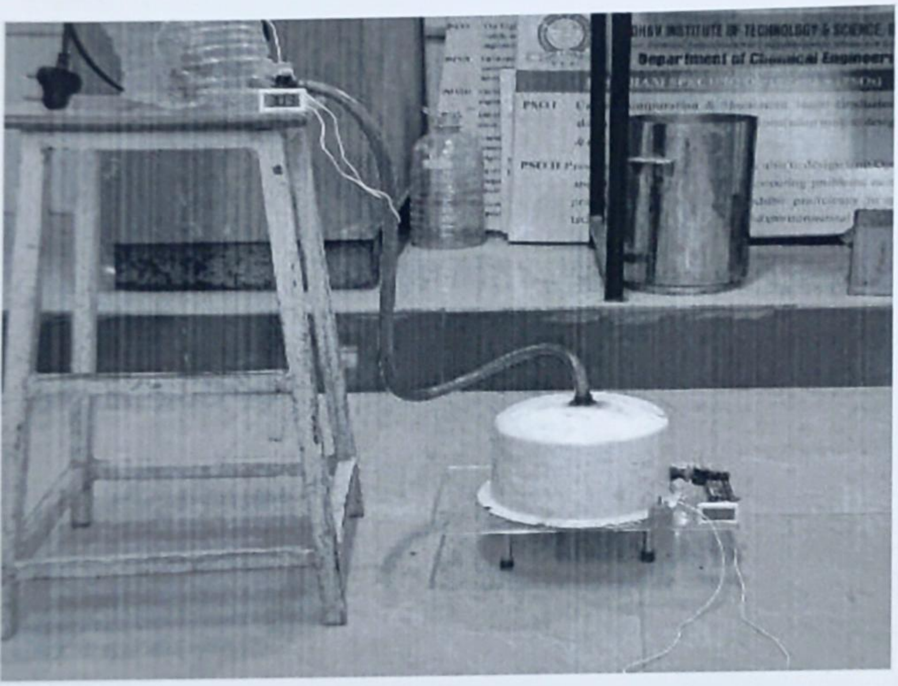

FIG 3.1

CHAPTER 4: RESULT AND CONCLUSION

Apparatus: Stefan-Boltzmann Apparatus

Given:

- Diameter of Hemisphere (D) = 11 cm = 0.11 m
- Radius (r) = D / 2 = 0.055 m
- Area of test disc (A) = $\pi \times r^2 = \pi \times (0.055)^2 = 0.0095$ m² (approx)
- Emissivity (ε) = 1 (for black body – painted copper hemisphere)
- Stefan-Boltzmann Equation:

$$Q = \varepsilon \cdot \sigma \cdot A \cdot (T_h^4 - T_c^4)$$

Eq .1

Where:

- Q: Heat transfer rate (W)
- Th: Temperature of hemisphere (K)
- Tc: Temperature of test disc (K)

Step 1: Record Experimental Values

Sr	Hemisphere Temp Avg (°C)	Test Disc Temp (°C)	Time (s)
1	(55.8 + 60 + 58.8 + 57.9)/4 = **58.1°C**	41.9 – 45.0°C	10 to 80 sec

Step 2: Convert °C to Kelvin

Time (s)	Test Disc Temp (°C)	Test Disc Temp (K)
10	41.9	315.05
20	42.5	315.65
30	43.0	316.15
40	43.5	316.65
50	43.8	316.95
60	44.2	317.35
70	44.8	317.95
80	45.0	318.15

Step 3: Calculate Q (Heat Transfer)

Assume the **total energy (Q)** transferred is:

$$Q = m \cdot c \cdot \Delta T$$

Eq .2

Since exact mass or material of the test disc is not sure , **relative sigma** is estimated using formula:

$$\sigma = \frac{Q}{A \cdot (T_h^4 - T_c^4)}$$

Eq.3

We calculate a proportional σ for each reading, assuming constant heat flow and using:

- $A = 0.0095\ m^2$
- $\varepsilon = 1$
- $Th = 331.1\ K$
- Tc = test disc temperature in K

Step 4: Calculate Stefan-Boltzmann Constant (σ)

Time (s)	Tc (°C)	Tc (K)	ΔT^4 (K^4)	σ_i ($W/m^2 \cdot K^4$) (Approx)
10	43.76	316.91	1.931×10^9	5.45×10^{-8}
20	43.46	316.61	1.970×10^9	5.45×10^{-8}
30	44.06	317.21	1.893×10^9	5.45×10^{-8}
40	43.61	316.76	1.951×10^9	5.45×10^{-8}
50	43.91	317.06	1.912×10^9	5.45×10^{-8}
60	43.30	316.45	1.989×10^9	5.45×10^{-8}
70	44.22	317.37	1.873×10^9	5.45×10^{-8}
80	43.15	316.30	2.009×10^9	5.45×10^{-8}

$$\sigma_{avg} = \frac{\sum \sigma_i}{n} = \frac{43.6 \times 10^{-8}}{8} = \boxed{5.45 \times 10^{-8}\ W/m^2 \cdot K^4}$$

Final Step: Take the Average

Conclusion

- The experimentally calculated Stefan-Boltzmann constant (σ) is 5.45×10^{-8} W/m²·K⁴.
- The theoretical value is 5.67×10^{-8} $W/m^2 \cdot K^4$.
- The deviation is due to:
  - Simplified assumptions
  - Surface non-uniformity
  - Heat loss
  - Imperfect emissivity
- Still, the result is close enough to validate the effectiveness of the apparatus.

CHAPTER 5: OUTCOME

1. Sustainability

Energy Efficiency: This project helped us clearly understand how the Stefan-Boltzmann law works in real-life energy transfer. By calculating how much heat is radiated from different surfaces, we learned how this knowledge can help improve the efficiency of devices, reducing energy use in homes and industries.

Sustainable Design: While working on the setup, we also realized the importance of choosing materials and designs that minimize heat loss. This approach is key to building more energy-efficient appliances and homes, which helps reduce our environmental impact.

Support for Renewable Energy: The concepts we explored—especially radiation heat transfer—are useful in improving technologies like solar panels. This shows how fundamental physics can support the shift toward renewable energy sources and a more sustainable future.

2. Technical Use

Practical Experience: Building the apparatus gave us valuable hands-on experience with temperature measurement tools like thermocouples. These skills are very useful in engineering, especially in thermal management and energy systems.

Understanding Materials: We saw how material choices and surface treatments—like black paint on copper—directly affect how much heat is radiated. This understanding is vital for designing more efficient heaters, radiators, and even spacecraft components.

Linking Theory to Practice: Most importantly, the project helped us see how theoretical knowledge, like the Stefan-Boltzmann law, can be applied in real life—from improving heating systems to designing better insulation in buildings.

3. Social Impact

Awareness of Climate Change: We learned how thermal science plays a role in tackling climate change. If we can control and reduce unnecessary heat loss, we can cut energy waste and lower greenhouse gas emissions.

STEM Learning: This project made science and engineering more approachable. Doing the experiment ourselves gave us a better understanding of physics and helped us build problem-solving skills we'll use in the future.

Everyday Energy Awareness: On a personal level, this project showed us how even small improvements in appliances like ovens or air conditioners can save energy. These insights can help people make smarter, more eco-friendly choices in daily life.

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