Indian Institute of Technology, Gandhinagar

Radiative Cooling

ME 334 Heat and Mass Transfer

Final Report & Group 4

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1 Introduction

Radiative cooling is the process by which a surface loses heat by emitting electromagnetic radiation, primarily in the infrared spectrum. This mode of heat transfer can occur without requiring a medium, making it effective even in a vacuum.

This project investigates and compares three cooling mechanisms: natural convection, forced convection, and radiative cooling, under different conditions. The study aims to analyze the cooling characteristics of each method.

2 Problem Statement

The project aims to compare the cooling performance of three methods: natural convection, forced convection, and radiative cooling. Using a heated copper plate as the test surface, the study will measure temperature changes and energy loss rates under different conditions.

3 Governing Equations and Assumptions

3.1 Radiative Cooling

- **Stefan-Boltzmann Law:**

$$E = \varepsilon\sigma(T^4 - T_\infty^4) \tag{1}$$

- **Total Radiative Heat Energy:**

$$Q_{rad} = \int \varepsilon\sigma A T^4 dt \tag{2}$$

- **Radiation Heat Transfer Rate:**

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_\infty^4) \tag{3}$$

  where:

  - $\sigma = 5.67 \times 10^{-8}$ W/mK (Stefan-Boltzmann constant)
  - $\varepsilon = 0.87$ for oxidized copper surface

- **Leak Rate:** From Ideal Gas equation $PV = mRT_\infty$ and further on differentiating on both sides w.r.t time, we get the below equation,

$$\frac{\Delta P}{\Delta t} = -\dot{m}_{\text{leak}}\frac{RT_\infty}{V} + \frac{mR}{V}\frac{dT_\infty}{dt}$$

where:

- P: Pressure inside the desiccator (Pa),
- $\dot{m}_{leak}$: Mass leakage rate of air (kg/s),
- R: Specific gas constant for air (J/kgK),
- T_∞: Ambient temperature inside the desiccator (K),
- V: Volume of the desiccator (m^3).

3.2 Natural Convection

- **Nusselt Number Correlation:**

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2 \tag{4}$$

- **Rayleigh Number:**

$$Ra = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{5}$$

- **Heat Transfer Coefficient:**

$$\overline{h_{nat}} = \frac{\overline{Nu}_L k}{L} \tag{6}$$

- **Natural Convection Heat Transfer Rate:**

$$\dot{Q}_{nat} = \overline{h_{nat}} A_s (T_s - T_\infty) \tag{7}$$

3.3 Forced Convection

- **Reynolds Number:**

$$Re = \frac{\rho u L}{\mu} \tag{8}$$

- **Nusselt Number Correlation:**

$$\overline{Nu}_L = 0.037 Re^{0.8} Pr^{1/3} \tag{9}$$

- **Heat Transfer Coefficient:**

$$\overline{h_{forced}} = \frac{\overline{Nu}_L k}{L} \tag{10}$$

- **Forced Convection Heat Transfer Rate:**

$$\dot{Q}_{forced} = \overline{h_{forced}} A_s (T_s - T_\infty) \tag{11}$$

3.4 Assumptions

To make our calculations manageable, we make these reasonable simplifications:

1. Steady State Condition

- The system reaches a stable state before we take measurements

2. Material Properties

- Uniform material properties throughout the copper plate
- Constant thermal conductivity and specific heat
- Uniform surface emissivity

3. Heat Transfer Simplifications

- One-dimensional heat conduction through the plate thickness
- Uniform surface temperature distribution
- The heating element transfers heat perfectly to the plate
- Edge effects don't significantly affect our results

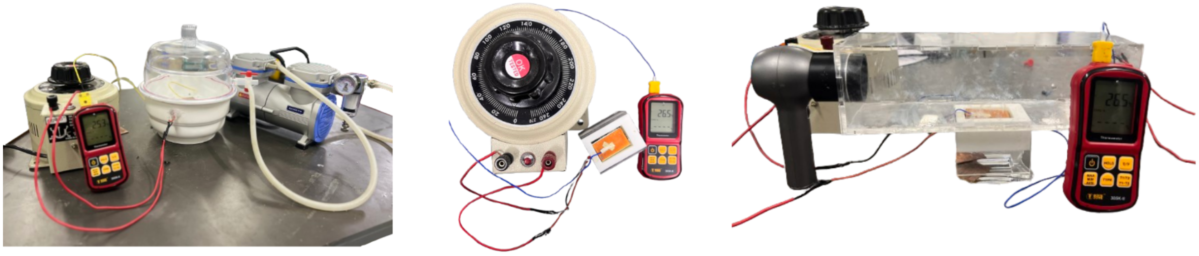
4. Environmental Considerations

- Constant ambient temperature during experiments
- Other objects don't radiate significant heat during convection tests
- Air properties don't change during each test
- For vacuum conditions: pressure low enough to neglect convection effects

5. Physical Setup Considerations

- We can treat the plate as perfectly flat
- Surface roughness doesn't significantly affect cooling
- When using a fan, airflow is uniform across the plate

4 Experimental setup



a) Radiative Cooling b) Natural Convection c) Forced Convection

Figure 1: Experimental Setup

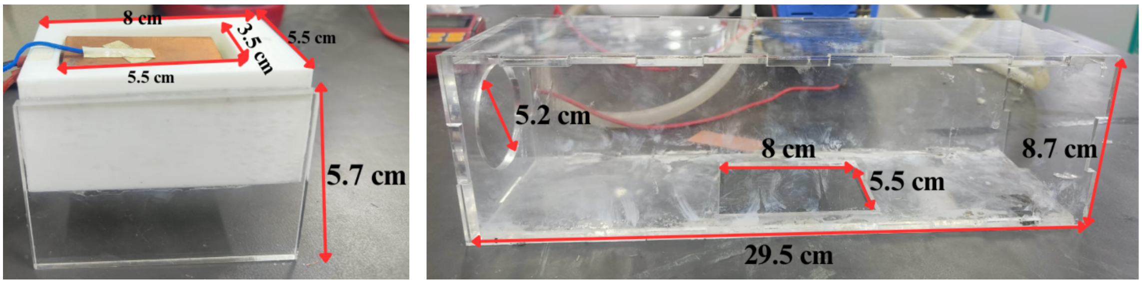


Figure 2: Experimental Setup with Dimension

4.1 Natural Convection

The experimental setup for natural convection includes a heating strip placed on a based table. The heating strip is connected to a voltage variac. A copper plate is fixed on the heating strip by an insulating tape. A thermocouple attached to a thermocouple deque is then placed on the copper to measure the surface temperature.

4.2 Radiative Cooling

The experimental setup for radiative heating includes a heating strip placed on an insulation foil inside the desiccator. The heating strip is connected to a voltage variac. A copper plate is fixed on the heating strip by an insulating tape. A thermocouple attached to a thermocouple deque is then placed on the copper to measure the surface temperature

4.3 Forced Convection

The experimental setup for the forced convection experiment consists of a Heating Plate and Copper Plate Holder, an Airflow Chamber, and a Voltage Variac. The holder securely accommodates the heating plate, copper plate, and a 0.5 cm thick insulation sheet, with overall dimensions of 5.5 cm (length), 3.5 cm (width), and 1.5 cm (depth). The Airflow Chamber, measuring 29.5 cm (length) 8.7 cm (width), is designed to direct airflow uniformly for effective forced convection. It features a 5.2 cm diameter airflow hole for unidirectional air passage and an 8 cm 5.5 cm heating plate slot at the bottom, ensuring the chamber surface aligns at the same height for optimal performance. The Voltage Variac powers the heating plate via two wire terminals: the red terminal (+ve) connects to the red wire, while the black terminal (-ve) connects to the black wire, facilitating precise voltage control to heat the copper plate.

5 Experimental Methadology

5.1 Natural Convection

- The heating pad was connected to the power supply and the voltage variac.
- The K-type thermocouple was connected to the surface of the copper plate to monitor its temperature.
- The ambient temperature was noted.
- The voltage variac was set to 40V and turned on to ensure the copper plate was heated uniformly.
- The copper plate was allowed to heat until a steady temperature was reached. This serves as the initial condition for the natural cooling process.
- Once the copper plate reached the set temperature, the power supply was disconnected to stop the heating.
- The temperature drop was then recorded manually at regular time intervals of 1 minute using the thermocouple.
- The recorded temperature data was used to plot the Temperature vs. Time curve for natural convection.
- The readings were taken until the temperature reached a nearly constant value for an extended period.

5.2 Forced Convection

- Once the experimental setup was made, the heating strip was connected to the power supply, which was kept at 40V. This is used to heat the copper plate.
- A K-type thermocouple was used to monitor the temperature of the copper plate.
- The copper plate was heated to a predefined temperature while keeping the Variac powered on.

5.3 Radiative cooling

- The heating pad was connected to the power supply and the voltage variac.
- The K-type thermocouple was connected to the surface of the copper plate to monitor its temperature.
- The ambient temperature was noted.
- The voltage variac was set to 40V and turned on to ensure the copper plate was heated uniformly.
- The copper plate was allowed to heat until a steady temperature was reached. This serves as the initial condition for the natural cooling process.
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6 Results

The data was collected by monitoring temperature variations over time for different configurations and parameters. The results are visualized through a series of plots, which highlight key trends and provide insight into the behavior of the cooling systems. Each plot represents specific experimental setups and conditions, as detailed below:

- Figure 3 showcases the temperature profiles for individual cooling methods. The plots for free convection, radiative cooling, and forced convection demonstrate their unique thermal responses and cooling patterns over time.
- Figure 4 provides a comparative analysis of the three cooling methods in a single graph. This allows for a direct evaluation of their cooling rates and efficiency under similar experimental conditions.
- Figure 5 explores additional experimental scenarios, going beyond the primary problem statement.

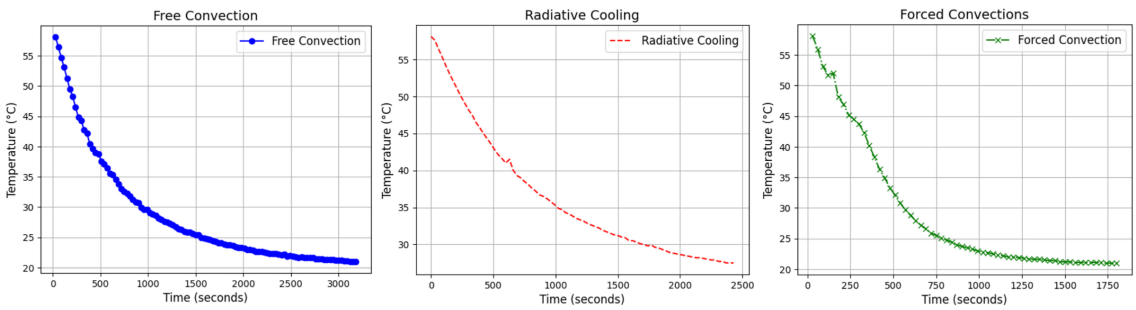


Figure 3: Plot of each Cooling methods

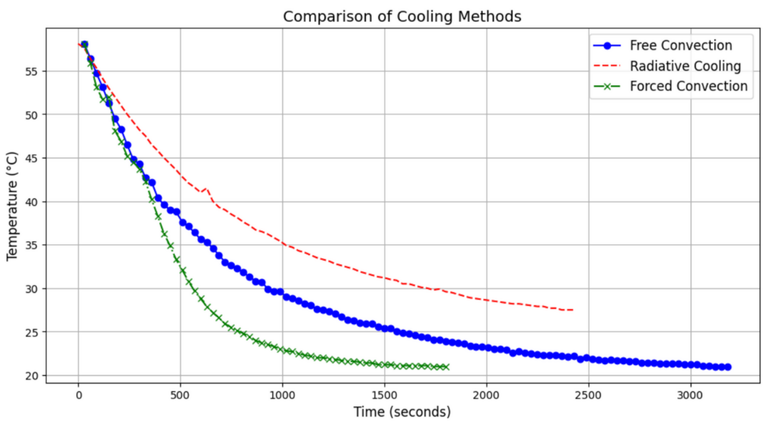
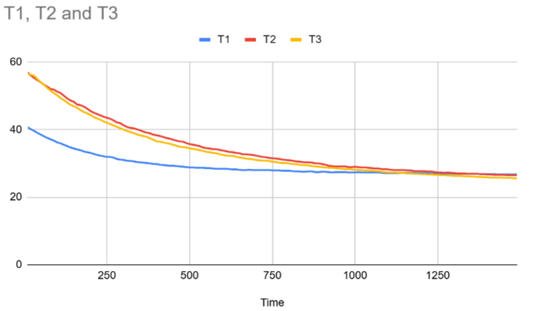
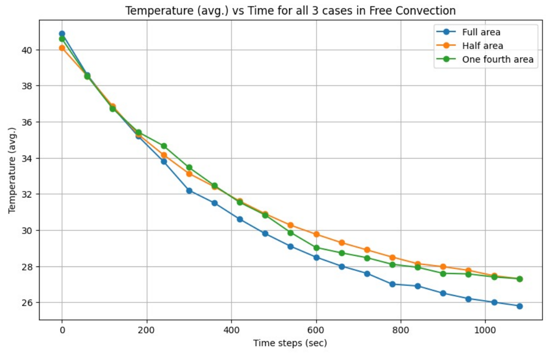


Figure 4: Comparison of Cooling methods

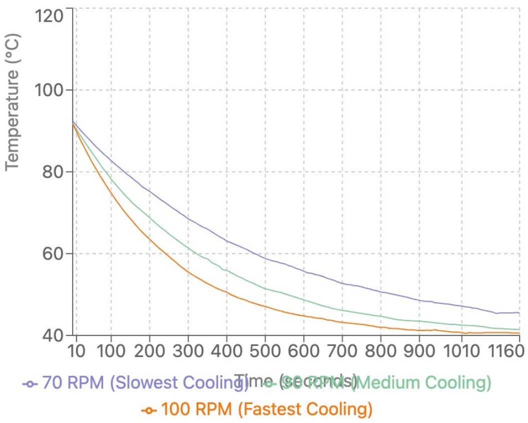
Plots beyond Problem Statement



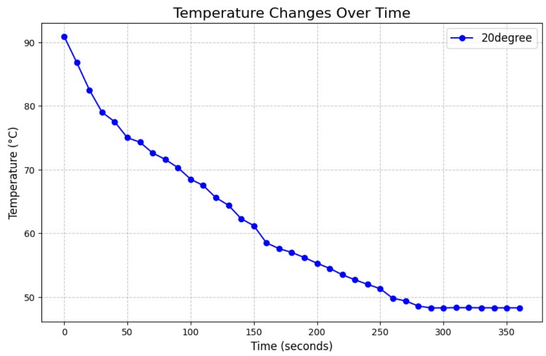
(a) Free Convection for different angles $T_1 = 90°$, $T_2 = 0°$, $T_3 = 20°$.



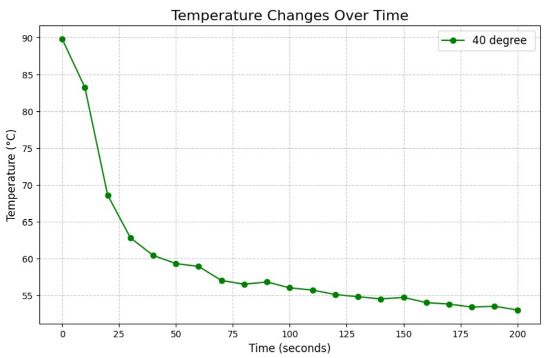
(b) Free convection for different lengths.



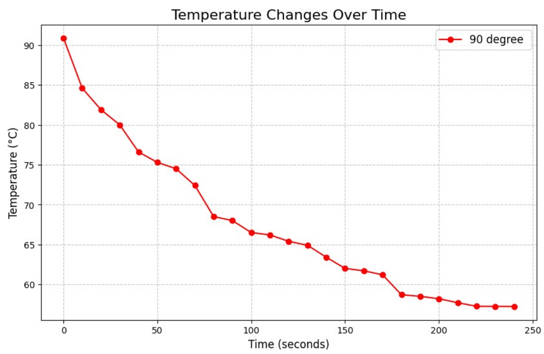
(c) Forced convection for different fan speeds.



(d) Forced convection for when fan source is kept at angle of 20°



(e) Forced convection for when fan source is kept at angle of 40°



(f) Forced convection for when fan source is kept at angle of 90°

Figure 5: Summary of free and forced convection results.

7 Discussion

7.1 Natural Convection Analysis

Effect of Angle

Data was collected for different angles (90, 0, and 20) to study radiative cooling.

- At **90**, the temperature drops faster due to efficient hot air rise and stronger convection, facilitating greater heat transfer from the copper plate to the surroundings.
- At **20**, the temperature drop rate was moderate as the airflow was less smooth.
- At **0**, the slowest temperature drop was observed, reflecting the weakest convection effect.

Effect of Length

Data was collected for various lengths: T_1: Measured at $L/4$, T_2: Measured at $L/2$, T_3: Measured at $3L/4$.

Smaller areas (e.g., $L/4$) lose less heat due to reduced surface exposure, causing slower cooling. Larger areas (e.g., $3L/4$) lose more heat energy due to increased surface exposure, leading to faster cooling.

7.2 Forced Convection Analysis

Effect of Fan Speed

Data was collected at different fan speeds.

- At low speeds, the airflow was less, resulting in slower heat dissipation.
- At high speeds, airflow increased, leading to faster heat dissipation.

7.3 Radiative Cooling Analysis

The radiation plot indicates that radiation plays a significant role at higher temperatures, as thermal radiation is proportional to the fourth power of the surface temperature (Stefan-Boltzmann law). The steepness of the radiative cooling curve at the beginning aligns with this principle, where higher initial temperatures lead to a higher radiative heat loss rate. As the temperature drops, radiative cooling becomes less significant because the temperature difference with the surroundings decreases. The curve flattens over time, reflecting the diminishing effect of radiation at lower temperatures. Thus, radiative cooling exhibits greater efficiency initially but converges with free convection over extended durations as the radiative contribution diminishes.

8 Novelty

8.1 Rate of Energy Lost in Natural Convection

Thermal Properties for $T_\infty \approx 300\,\mathrm{K}$

$$\begin{aligned}
\rho &= 1.1614\,\mathrm{kg\,m^{-3}}, \quad C_p = 1.007\,\mathrm{kJ\,kg^{-1}\,K^{-1}},\\
\mu &= 184.6\times10^{-7}\,\mathrm{N\,s\,m^{-2}}, \quad \nu = 15.89\times10^{-6}\,\mathrm{m^2\,s^{-1}},\\
k &= 26.3\times10^{-3}\,\mathrm{W\,m^{-1}\,K^{-1}}, \quad \alpha = 22.5\times10^{-6}\,\mathrm{m^2\,s^{-1}},\\
\mathrm{Pr} &= 0.707, \quad \beta = 3.22\times10^{-3}\,\mathrm{K^{-1}}.
\end{aligned}$$

Full Area Case

Table 1: Results for Full Area Case

Parameter	Expression / Formula	Result
Rayleigh Number (Ra_L)	$\frac{g\,\beta(T_s-T_\infty)L^3}{\nu\,\alpha}$	$3.25\times10^9 L^3$
Nusselt Number (Nu_L)	As per formula	Top: 1.947, Sides: 1.38, Front: 1.37
Heat Transfer Coefficient (h)	$\frac{Nu_L\,k}{L}$	Top: $5.63\,\mathrm{W\,m^{-2}\,K}$, Sides: 7.4, Front: 7.616
Heat Loss ($\dot{q}$)	$hA_s(T_s - T_\infty)$	Total: $0.71\,\mathrm{W}$

Half Area Case

Table 2: Results for Half Area Case

Parameter	Expression / Formula	Result
Rayleigh Number (Ra_L)	$\frac{g\,\beta(T_s-T_\infty)L^3}{\nu\,\alpha}$	$1.73\times10^9 L^3$
Nusselt Number (Nu_L)	As per formula	Top: 1.79, Bottom: 1.72, Sides: 1.30, Front: 1.29
Heat Transfer Coefficient (h)	$\frac{Nu_L\,k}{L}$	Top: $5.17\,\mathrm{W\,m^{-2}\,K}$, Bottom: 6.79, Sides: 69.77, Front: 70.68
Heat Loss ($\dot{q}$)	$hA_s(T_s - T_\infty)$	Total: $0.45\,\mathrm{W}$

Quarter Area Case

Table 3: Results for Quarter Area Case

Parameter	Expression / Formula	Result
Rayleigh Number (Ra_L)	$\frac{g\,\beta(T_s - T_\infty)L^3}{\nu\,\alpha}$	$1.27 \times 10^9 L^3$
Nusselt Number (Nu_L)	As per formula	Top: 1.72, Bottom: 1.69, Sides: 1.26, Front: 1.26
Heat Transfer Coefficient (h)	$\frac{Nu_L\,k}{L}$	Top: 4.97 W m^{-2} K, Bottom: 5.48, Sides: 67.62, Front: 69.03
Heat Loss ($\dot{q}$)	$hA_s(T_s - T_\infty)$	Total: 0.34 W

8.2 Rate of Energy Lost in Forced Convection

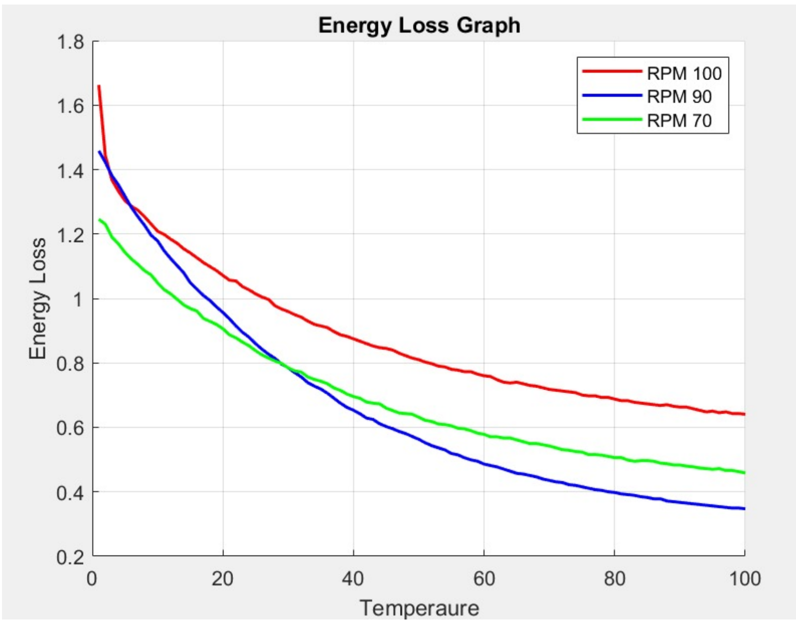


Figure 6: Heat Loss in Forced Convection

8.3 Rate of Energy Lost in Radiative Cooling

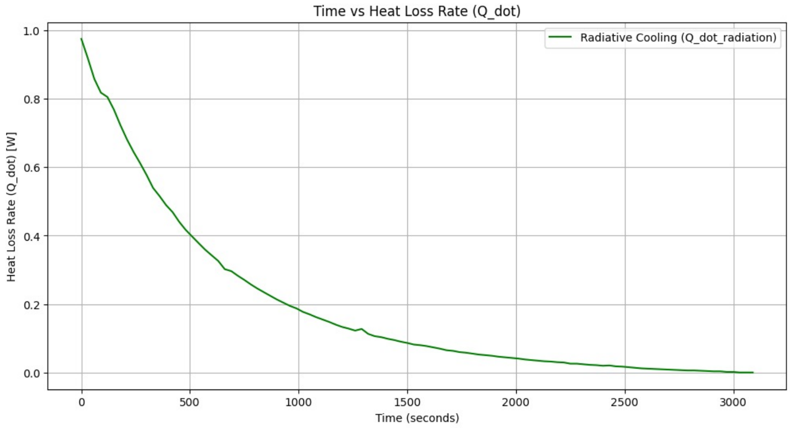


Figure 7: Heat Loss in Radiative cooling

At steady State $\dot{Q} = 0.975W$ and Area $= 0.001582\ m^2$. **Note:** surface area is taken for copper plate except for bottom as it is insulated.

8.4 Leak Rate in Radiative cooling

Given the equation:

$$\frac{\Delta P}{\Delta t} = -\dot{m}_{\text{leak}} \frac{RT_\infty}{V} + \frac{mR}{V}\frac{dT_\infty}{dt}$$

Second term $\frac{mR}{V}\frac{dT_\infty}{dt}$ will vanish as in steady state, $\frac{dT_\infty}{dt} = 0$

$$\text{Hence, } \dot{m}_{\text{leak}} = -\frac{V}{RT_\infty}\frac{\Delta P}{\Delta t}$$

Table of Parameters

Parameter	Value	Units
Initial Pressure(P_{initial})	$15,000$	Pa
Final Pressure(P_{final})	$13,550$	Pa
Temperature(T_∞)	299	K
Time Interval(Δt)	10	min
Volume(V)	0.00566337	m^3
Pressure Drop(ΔP)	$-1,450$	Pa

On substituting all values;

$$\dot{m}_{\text{leak}} = -(6.6 \times 10^{-8}) \times (-2.4167) = 1.59 \times 10^{-7}\ \text{kg/s}$$

9 Critical analysis and Challenges faced

9.1 Natural Convection

Conducting natural convective cooling experiments under varying ambient temperatures is challenging due to fluctuations in environmental conditions like temperature and humidity, which change dynamically over time and location. To address this, we attempted to simulate controlled ambient conditions using a chamber equipped with a heater and humidifier, managed via Arduino for precise temperature and humidity control. However, the results obtained were inconsistent and inaccurate, highlighting unanticipated challenges in replicating natural conditions accurately.

9.2 Forced Convection

In forced convection experiments, several challenges arise, including achieving uniform airflow and maintaining a consistent temperature gradient. Variations in fan speed and airflow, improper heat source placement, and difficulties in measuring air velocity can lead to inaccuracies. Additionally, system vibrations, leakage issues, and environmental factors like temperature and humidity fluctuations can distort results. Accurate calibration of the fan and ensuring precise control of the heat transfer coefficient are also critical for obtaining reliable data.

9.3 Radiative cooling

Maintaining a proper vacuum is critical for accurate radiative cooling measurements. Leaks in the system, particularly at connections between the vacuum pump, desiccator, and pipes, can compromise the vacuum, requiring repeated troubleshooting and adjustments.

10 Future Work

- We can perform the experiment with different materials, such as aluminum and steel, to gain a better understanding of radiative cooling, as different materials have unique surface properties like thermal conductivity and emissivity.
- By using computational fluid dynamics (CFD) simulation models, we can compare the results with experimental data. CFD provides a more detailed and dynamic analysis of cooling processes, enabling visualization of airflow, temperature distribution, and turbulence, which are not always easily observed experimentally.
- Experiments can be conducted on different surface types, such as hydrophobic, superhydrophobic, and hydrophilic surfaces, to study their impact on cooling performance.

11 Contribution

- **Astitva Aryan (22110041):** I contributed significantly to the radiative cooling part of the project by conducting experimental readings and working on the setup structure, which was later redesigned. I wrote and applied governing equations with key assumptions for natural convection, forced convection, and radiative cooling. Additionally with some research, I suggested ideas for further explorations, like testing the plate at different angles to the horizontal. Also, I contributed to the reports.
- **Pasala Greeshma (22110182):** I have contributed to the project in performing experiment for different voltage and taken reading. I have taken reading for natural convection and forced convection. I participated in group meeting and disscusions. I have done some exploration for the experiment and serched for some resources.
- **Dharavath Mahesh (22110073):** Assisted in designing and creating prototypes. Contributed to building the setup and conducting experiments to obtain force conversion readings. Contributed to report preparation by explaining the setup, detailing the force conversion experiment, and presenting the findingseffectively.
- **Abhinav Singh Yadav (22110011):** Helped in maintaining bom, gave various ideas to explore(nobility), took readings for natural convection, took all the readings for the area reduction and also proposed that idea, also took readings for radiative cooling and helped in sealing the dessicator, helped in-reportmaking
- **Harsh Chhapru (24120007):** Collected Data in Radiative Cooling, Revised the experimental setup in Radiative cooling, helped in the calculation in forced convection, In report wrote the procedure for Radiative cooling and some governing equation for Radiativecooling
- **Sridhar Thakur (22110257):** Researched materials online and prepared the Bill of Materials (BOM), Designed the complete experimental setup using CAD, Experimental setup construction (initial, intermediate, and final versions), Collected data for forced convection experiments, including variable fan speeds, and assisted in data plotting and analysis, Coordinated with the mentor regularly to verify findings, Contributed equally to writing theprojectreport.

- **Gamre Ketki (22110082):** Did research on futher explorations in the experiment Assisted in conducting natural convection at different angles and different contact area experiments Prepared copper surfaces for the experiments Contributed to the report by writing detailed sections on the experimental procedure, critical analysis, and challenges encountered during natural convection testing, and results for radiativecooling
- **Mallepogula Charanteja (22110136):** Explored required materials, and contributed to compiling the phase 1 report. I contributed to fix the experimental setup for natural/forced convection, performed natural and forced convection experiments, and calculated the rate of energy loss for area reduction cases in naturalconvection.
- **Shaurykumar Patel (22110241):** I contributed to every phase of the project. In Phase 1, I participated in ideating the experimental setup and compiled its report. During Phase 2, I actively worked on building the experimental setup, coordinated the teams efforts, and edited the video for the submission. In Phase 3, I reconstructed the forced convection setup from scratch, addressed supervisor-suggested changes, resolved a leakage issue in the radiative cooling setup, and collected readings for radiative cooling. Additionally, I compiled the final report and organized all data plots for the final submission, ensuring a cohesive presentation ofourfindings.

12 Acknowledgement

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Finally, we would like to thank IIT Gandhinagar for offering us this opportunity through the course.

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