ME-207
FLUID DYNAMICS
OPEN-ENDED PROJECT
THERMAL MANAGEMENT SYSTEM USING CONVECTIVE AIR FLOW
GROUP-9

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Abstract: Thermal management systems are integral to numerous industries, ensuring efficient heat dissipation from electronic devices and machinery. In this experiment, our aim was to design and evaluate a thermal management system utilizing convective airflow. The core components comprised an acrylic duct, a controllable blower, an anemometer for airflow measurement, and a centrally positioned heat plate heated electrically. Our primary objective was to observe how convective air flow influenced the cooling efficiency of the heat plate. By analyzing temperature data collected at various duct points, we aim insights into the system's ability to dissipate heat effectively. Controlled variables included blower speed, electrical current to the heater, and temperature readings along the duct. By exploring convective airflow's practical application for thermal regulation, our findings hold implications for industries necessitating efficient heat dissipation solutions.

I.INTRODUCTION

Thermal management systems play a critical role in various industries, ensuring the efficient dissipation of heat generated by electronic devices and machinery. In this experiment, we aimed to design and evaluate a thermal management system utilizing convective air flow. The system's core components included an acrylic duct, a blower with adjustable speed, an anemometer for measuring outlet wind velocity, and a centrally located heat plate heated by electrical current.

The primary objective was to observe how convective air flow, facilitated by the blower, influenced the cooling efficiency of the heat plate. By analyzing temperature data collected at different points within the duct, we aim to understand the system's ability to dissipate heat effectively.

The experimental setup allowed us to control variables such as blower velocity, electrical current to the heater, and temperature readings at various locations along the duct. By recording these parameters during the experiment, we aimed to draw conclusions about the system's performance in maintaining thermal equilibrium and managing heat transfer.

This report details the experimental procedure, data collection methods, analysis techniques, and the results obtained from the thermal management system. Through this investigation, we aim to contribute insights into the practical application of convective air flow for thermal regulation, with potential implications for industries requiring efficient heat dissipation solutions.

II.OBJECTIVE

The objective of this experiment was to design, construct, and analyze a thermal management system utilizing convective air flow. The specific goals were as follows:

1. System Design and Construction:
   - Develop a thermal management system comprising an acrylic duct, a blower with adjustable speed, an anemometer for measuring outlet wind velocity, and a centrally located heat plate.
   - Ensure the duct's design facilitates smooth airflow to optimize heat dissipation.
2. Heat Plate Temperature Analysis:
   - Heat the centrally located plate using variable electrical current until it reaches a steady state temperature.
   - Record the temperature at the plate's surface and the surrounding air to establish baseline values.
3. Convective Air Flow Investigation:
   - Activate the blower at a constant velocity to induce convective air flow within the duct.

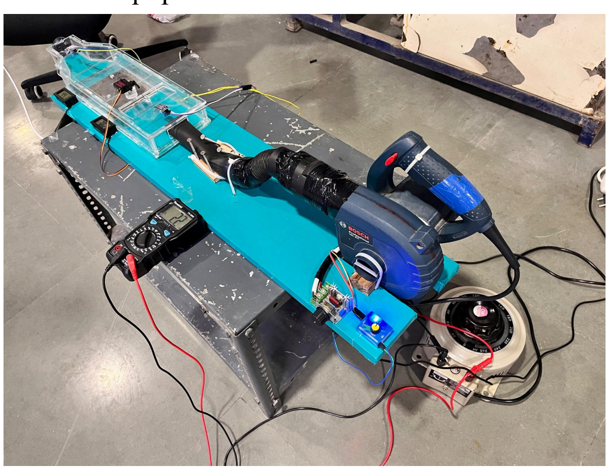
- Measure and record temperatures at various points along the duct, including the plate surface and outlet air.

4. Data Collection and Analysis:
   - Record temperature data over time to observe the cooling behavior of the heat plate.
   - Analyze temperature differentials between the plate, inlet air, and outlet air to assess the system's heat transfer efficiency.
5. Efficiency and Effectiveness Assessment:
   - Calculate the heat dissipation efficiency of the system based on the experimental data.
   - Compare the effectiveness of convective air flow in cooling the heat plate to passive cooling methods.

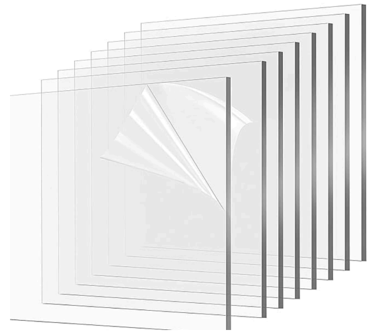
By achieving these objectives, we aimed to gain insights into the effectiveness of convective air flow as a method for thermal management. The experiment sought to provide practical data that could inform the design of more efficient heat dissipation systems in various industrial applications.

III.EXPERIMENTAL SETUP

Materials and Equipment



1. Acrylic Duct:
   - Material: 5mm thick acrylic sheet.



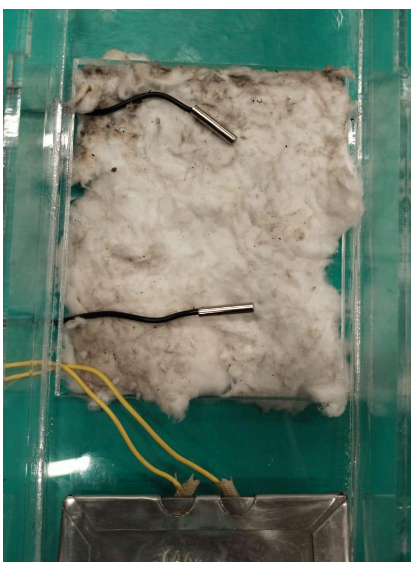
   - Dimensions:
     - Height: 35mm (inner height of the duct).
     - Various cuts had been made but the length of the flow is approx 423mm and breadth of the duct is 110mm and at exit the width is 50mm a detailed diagram is shown ahead.
2. Blower:

   - Type: Blower with fixed speed
   - Control: Speed controlled using an electronic dimmer.
   - Settings: 620 W power rating, brand: BOSCH
3. Anemometer:

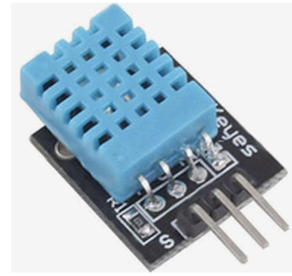
   - Device to measure outlet wind velocity.

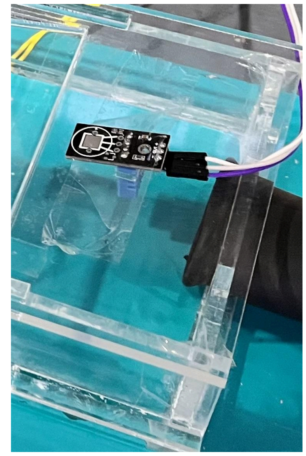
- Used to quantify the airspeed within the duct and also at the inlet using continuity equation.

4. Heat Plate:
    - Located centrally within the duct.
    - Material: steel
    - Size: 100mm x 120mm
    - Heated using AC current.
    - Control: Heater controlled using a Variac.
5. Temperature Sensors:
    - Thermocouples: 2 probes placed below the heat plate for direct temperature measurement.



- DHT Sensor: Placed at the inlet and outlet on the upper surface of the duct for air temperature measurement.





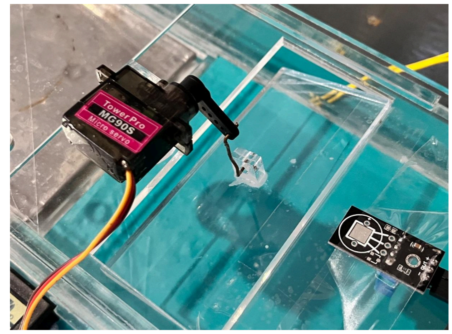
- Data Acquisition: Arduino Uno used to read and record sensor data.

6. Power Supply:
    - Used to provide electrical current to the heater and blower.
    - Variac: Used to control the heater.

- Dimmer: Used to control the blower speed.

7. Insulation
   - Cotton wool had been placed below the plate to make it adiabatic.

8. Flap to control air direction
   - The flap was controlled using servo motor



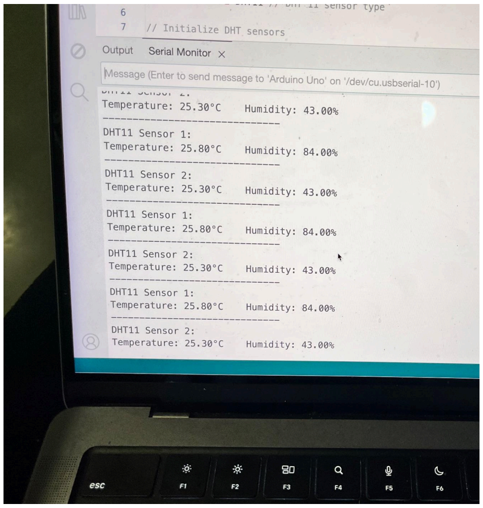
Experimental Procedure

1. Duct Assembly:
   - Constructed the acrylic duct with a 5mm thickness and a height of 35mm to provide a confined airflow path.
   - Ensured proper sealing to prevent air leakage using tape.
2. Heater Activation:
   - Applied controlled voltage using a Variac to the heat plate until it reached a steady state temperature the voltage and the current drawn by the heater was measured using voltmeter

.

   - Recorded the start temperature of the heat plate (T_plate(start)).
   - Also recorded the timing of the heating duration.
3. Blower Operation:
   - Turned on the blower with a variable speed controlled by an electronic dimmer.
   - Maintained a constant velocity for the blower.
   - We could achieve the inlet speed of air ranging from 20 m/s to 45 m/s.
4. Data Collection:

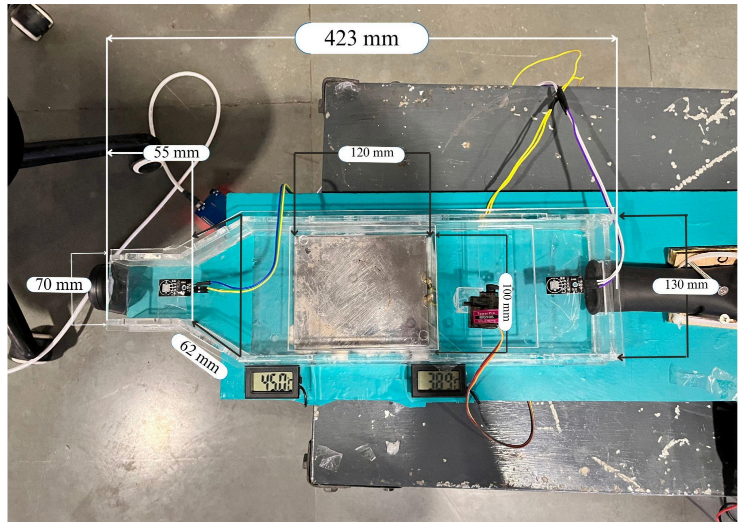
- Recorded temperature readings at specified time intervals (e.g., every 5 seconds) using Arduino Uno or sometimes manually.

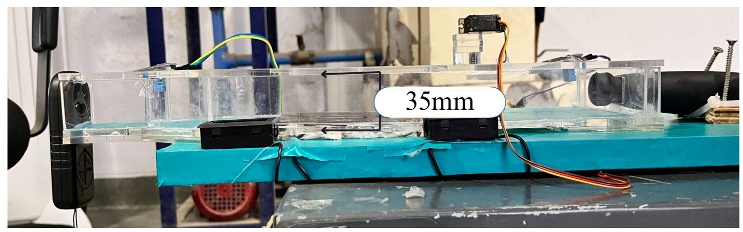


- Recorded temperatures included:
  - T_plate(end): Temperature at the end of the heat plate.
  - T_air_Outlet: Temperature of the air at the outlet.
  - T_air_Inlet: Temperature of the air at the Inlet.
  - T_plate(start): Start temperature of the heat plate (assumed to be the same as T_plate(end) after heating).

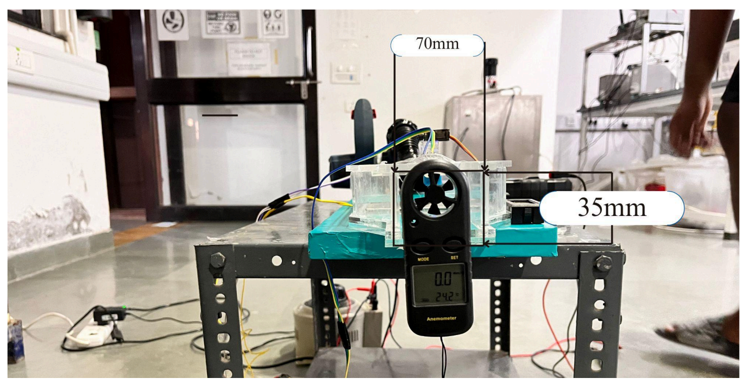
5. Data Recording Duration:
   - Continued data collection until the heat plate cooled down to the inlet air temperature.
6. Controlled Variables:
   - Kept the blower velocity constant throughout the experiment.
   - Maintained a fixed electrical current for the heater using the Variac but while cooling we had turned off the variac.
7. Safety Measures:
   - Adhered to safety protocols for electrical equipment.
   - Ensured proper ventilation and handling of hot components.

Experimental Diagram

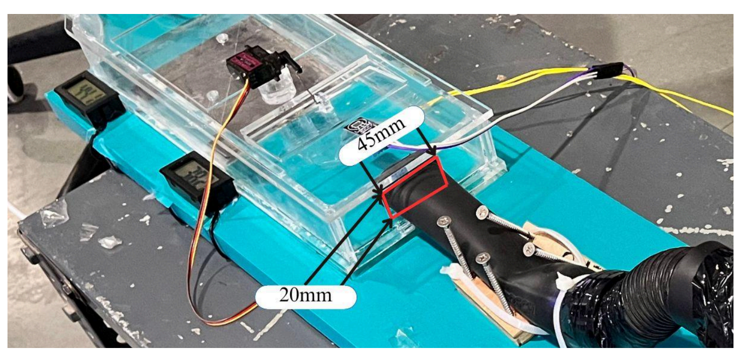




Exit area-



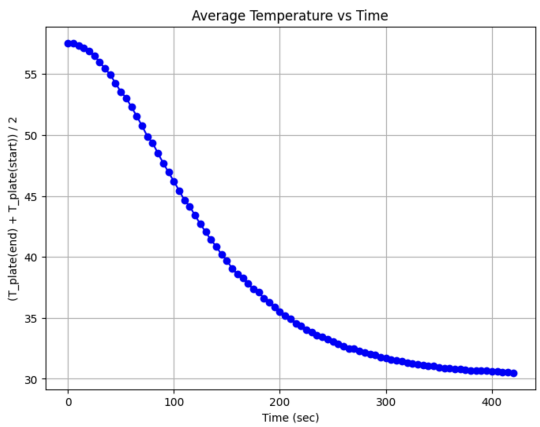
Inlet area-



III.RESULTS AND DISCUSSION

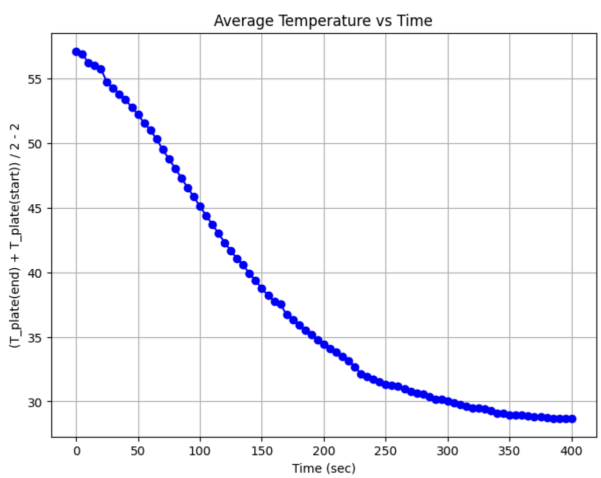
We had run the setup for different flow rate and observed the colling rate of the plate and plot the temperature of the plate vs the time.

V_in = 25.375m/s | T_steady = 61 degree celsius |Flap closed

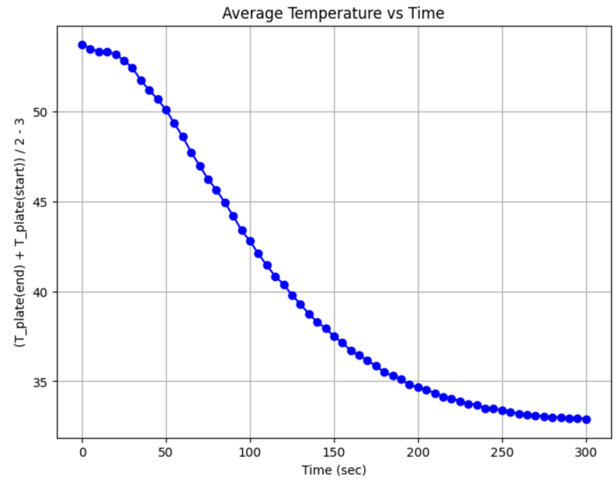


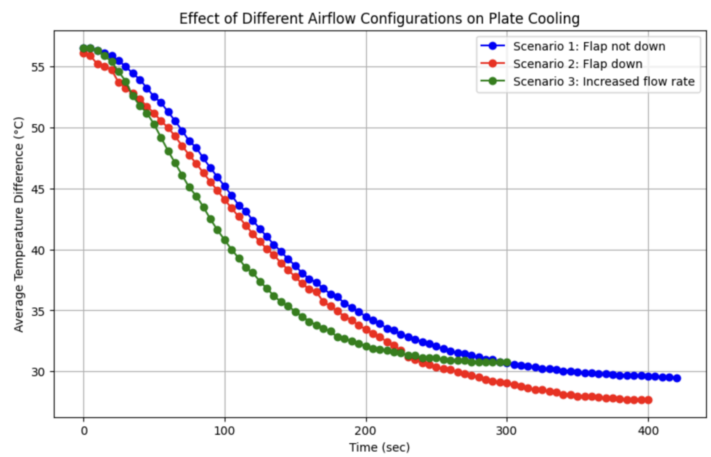
Now for the same steady state temperature we had run the experiment but this time we had lowered the flap at 30 degree.

V_in = 25.375m/s | T_steady = 61 degree celsius | Flap down



V_in = 40.5m/s | T_steady = 61 degree celsius | Flap closed



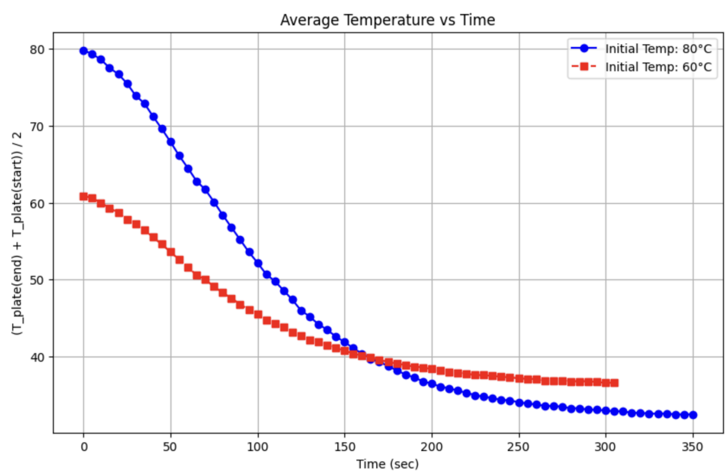


1. Scenario 1 - Flow Rate Variation: The graph illustrates the cooling behavior of a plate subjected to a constant flow rate of cooling fluid at 25.375 m/s. The blue curve represents the cooling process with the flow rate maintained at 25.375 m/s. As time progresses, the average temperature of the plate decreases gradually, indicating the effectiveness of the cooling process. The plateau observed towards the end of the cooling period suggests that the plate approaches thermal equilibrium with the surrounding environment. This scenario demonstrates the cooling behavior of the plate under constant flow rate conditions.
2. Scenario 2 - Flap Position Variation: The graph depicts the cooling behavior of a plate with the flow rate maintained at 25.375 m/s, while the position of the flap controlling the airflow is altered. The blue curve represents the cooling process with the flap

positioned downward at 30 degrees, allowing direct airflow over the plate. As time progresses, the average temperature of the plate decreases more rapidly compared to the scenario with the flap in the default position. This observation suggests that altering the flap position enhances the cooling efficiency by facilitating direct airflow over the plate.

3. Scenario 3 - Flow Rate Variation: The graph illustrates the cooling behavior of a plate subjected to an increased flow rate of cooling fluid, raised from 25.375m/s to 40.5 m/s. The blue curve represents the cooling process with the flow rate increased to 40.5 m/s. As time progresses, the average temperature of the plate decreases more rapidly compared to the scenario with the flow rate maintained at 25.375 m/s. This observation indicates that increasing the flow rate enhances the cooling efficiency, resulting in a faster decrease in the plate temperature.

Now for same flow rate we had cooled the plate from 2 different temperature. One from 60 and other 80 with inlet velocity of 35m/s.



The graph illustrates the cooling behavior of a plate subjected to a constant flow rate of cooling fluid, with initial temperatures of 80°C and 60°C. Each curve represents the average temperature of the plate over time, calculated as the average of the starting and ending temperatures at each time interval. The blue curve represents the cooling process starting from an initial temperature of 80°C, while the red dashed curve depicts the cooling process starting from an initial temperature of 60°C. As time progresses, both curves show a gradual decrease in temperature, indicating the plate's cooling response to the cooling fluid. Comparing the two curves, it's evident that the plate starting at a higher initial temperature cools down more slowly compared to the plate starting at a lower initial temperature. This observation highlights the influence of the initial temperature on the cooling rate of the plate under constant cooling conditions.

Energy Balance and Heat Transfer Coefficient

We had tried our level best to study from [1] this but we can't really comment on the accuracy.

1. Assumptions: we assumed constant fluid density, dynamic viscosity, and characteristic length of the plate.
2. Calculation of Reynolds number (Re): Reynolds number indicates the flow regime. In laminar flow, Re is typically low. It's calculated using the density, velocity, and characteristic length of the flow, divided by dynamic viscosity.
3. Observation of laminar flow: determined that the flow over the plate is laminar, meaning the fluid moves smoothly in parallel layers.

4. Energy rate (mdot * cp * ΔT): This equation represents the rate of heat transfer from the plate to the fluid. mdot is the mass flow rate, cp is the specific heat , and ΔT is the temperature difference between the plate and the flow.
5. Calculation of Nusselt number (Nu):The Nusselt number for a hot plate can be calculated using the formula given below. It's a dimensionless number and is typically determined empirically or through correlations. In laminar flow over a flat plate, it can be calculated using correlations like those found in textbooks by Incropera.

$$N_u = 0.023 \times R_e^{0.8} \times P_r^{0.3}$$

6. Determination of convective heat transfer coefficient (h): The formula is commonly used to calculate the convective heat transfer coefficient (

$$h = \frac{N_u \times D}{K}$$

- Nu is the Nusselt number,
- D is a characteristic length or diameter,

- k is the thermal conductivity of the fluid.

7. The equation $Q = hA(T_{avg} - T)$ represents the theoretical calculation of heat transfer using Newton's law of cooling, where:
   - Q is the rate of heat transfer (in watts),
   - h is the convective heat transfer coefficient (in watts per square meter per degree Celsius or Kelvin),
   - A is the surface area through which heat is transferred (in square meters),
   - T_average is the average temperature of the surface (in degrees Celsius or Kelvin), and
   - T is the temperature of the surrounding fluid or medium (in degrees Celsius).

The Reynolds number (Re), a measure of flow regime, was computed to ascertain laminar flow, indicating smooth, parallel movement of the fluid layers. This was achieved by dividing the product of fluid density, velocity, and characteristic length by dynamic viscosity.

$$D = \frac{4\times A}{P}$$

Where, P is the perimeter and A is the cross sectional area of the plate.

$$A=10\times12\times10^{-4}=1.2\times10^{-2}\ m^{2}$$

$$D = \frac{4\times1.2\times10^{-2}}{2(10+12)\times10^{-2}}=0.109 \text{ m}$$

1

Flow rate = 60	volt = 30	current=0.225

T_plate(end)	T_plate(start)	T_air_Outlet
60.9	52.2	31.9

So

$$T_{avg} = \frac{T\_plate(end)+T\_plate(start)}{2} = \frac{60.9+52.2}{2} = 56.55 \text{ (in degree celsius)}$$

So at T =31.9 ==> μ=0.7 mpa-s

$$R_e = \frac{\rho v D}{\mu}$$

$$R_e = \frac{1.2\times16.66\times0.109}{0.7\times10^{-3}} = 3113.04$$

$$R_e = 3113.04 \text{ (laminar flow)}$$

Utilizing the equation for energy rate, representing the heat transfer from the plate to the fluid, and the calculation of the Nusselt number (Nu) via the empirical formula, we estimated the convective heat transfer coefficient (h). This coefficient, crucial for determining heat transfer efficiency, was derived using the Nusselt number, characteristic length, and thermal conductivity of the fluid.

$$N_u = 0.023 \times R_e^{0.8} \times P_r^{0.3}$$

At T =31.8 $\Rightarrow$ $P_r = 0.7$

$$N_u = 0.023 \times (3113.04)^{0.8} \times (0.7)^{0.3}$$

$$N_u = 12.877$$

And we know that

$$h = \frac{N_u\times D}{K}$$

Where K=0.02

$$h = \frac{12.877\times0.109}{0.02}$$

$$h = 2.3627 \ \frac{W}{m^2 k} \quad \text{(Theoretical)}$$

Further, we applied Newton's law of cooling to theoretically compute the rate of heat transfer (Q), considering the average temperature of the surface (T_avg), the temperature of the surrounding fluid (T), and the surface area through which heat is transferred (A). Additionally, we calculated the characteristic length (D) and cross-sectional area (A) of the plate.

For experimental validation, we measured the convective heat transfer coefficient (h_experimental) using voltage and current readings, and compared it with the theoretically calculated value (h_theoretical). Additionally, we determined the energy transferred using mass flow rate (mdot), specific heat (Cp), and temperature difference (ΔT).

Experimental

$$Q = hA(T_{avg} - T)$$

$$VI = hA(T_{avg} - T)$$

At

volt = 30	current=0.225

$$30 \times 0.225 = h \times 10 \times 12 \times 10^{-4}(113.9 - 31.9)$$

$$h = 6.859 \frac{W}{m^2 k} \qquad \text{(experimental)}$$

Energy

$$mdot = \rho A v$$

$$mdot = 1.2 \times 4.5 \times 2 \times 10^{-4} \times 16.67$$

$$mdot = 0.01799 \frac{Kg}{s}$$

$$Q = mdot \times C_p \times \Delta T$$

$$Qdot = 0.018 \times 1.007 \times (113.9 - 31.9)$$

$$Qdot = 1487.238 \text{ J}$$

Our findings indicate variations in the convective heat transfer coefficient (h) for different flow rates and configurations. The table summarizes the experimental results alongside the theoretical predictions for various flow rates and configurations.

V_{out} ($\frac{km}{h}$)	voltage(V)	Temperature of Hot plate(in celcius)	Flow rate(f) =AV ($\frac{m^3}{s}$)	$h_{theoretic}$	$h_{experime}$
60	30	79.8	291.725×10^{-4}	2.825	28.04
60	30	60.9	291.725×10^{-4}	2.3627	6.8593
47	20	61.3	228.375×10^{-4}	1.75	9.3164
47 flap down	22	62.5	228.375×10^{-4}	1.75	10.83
75	30	61.5	364.525×10^{-4}	2.3627	14.145

Our investigation into the energy balance and heat transfer coefficient provides valuable insights into the thermal behavior of the system under different conditions. The discrepancies between theoretical predictions and experimental observations highlight the complexities inherent in real-world applications. Further refinements in experimental procedures could enhance the accuracy of future studies in this domain.

IV.ERRORS

During the course of our experiment, we encountered several challenges and sources of error that may have influenced the accuracy and reliability of our results. It is important to acknowledge these limitations and consider their potential impact on the interpretation of our findings.

1. **Measurement Errors**: One of the primary sources of error in our experiment was associated with measurement inaccuracies. Despite our efforts to calibrate and validate the sensors and measurement

devices used, there may have been inherent errors in the readings obtained. Variations in sensor calibration, environmental conditions, and electrical interference could have contributed to measurement discrepancies.

2. **Experimental Conditions**: The controlled environment of our laboratory setup may not fully replicate real-world conditions encountered in practical applications. Factors such as ambient temperature fluctuations, air currents, and humidity levels could influence the performance of the thermal management system differently in real-world scenarios. Failure to account for these external variables may have introduced errors into our results.
3. **Assumptions and Simplifications**: In our analysis, we made several assumptions and simplifications to facilitate calculations and data interpretation. For example, we assumed constant fluid properties, uniform airflow distribution, and idealized heat transfer conditions. These simplifying assumptions may not fully reflect the complex and dynamic nature of heat transfer phenomena in real systems, leading to discrepancies between theoretical predictions and experimental observations.
4. **System Dynamics**: The dynamic behavior of the thermal management system, including transient effects during startup and shutdown periods, was not fully accounted for in our analysis. Rapid changes in temperature, airflow velocity, and heat generation could introduce uncertainties into our measurements and calculations, affecting the accuracy of our results.
5. **Human Error**: Lastly, the possibility of human error cannot be overlooked. Factors such as improper setup, procedural mistakes, and data recording errors may have occurred during the experiment, leading to inconsistencies or inaccuracies in the collected data.

Despite these challenges and limitations, we have endeavored to conduct our experiment with rigor and integrity, adhering to established protocols and best practices in experimental design. By acknowledging these sources of error and exercising caution in the interpretation of our results, we aim to maintain transparency and ensure the validity of our findings.

IV.APPLICATION & IMPLICATION

The findings of this study have several practical applications and significant implications in the field of thermal management and related areas. By investigating the cooling process of a heat plate under varying experimental conditions, valuable insights have been gained that can be applied in various domains:

1. Engineering and Design: The results of this study can inform the design and optimization of thermal management systems in engineering applications. Understanding the cooling dynamics of heat plates under different airflow conditions can aid engineers in developing more efficient heat dissipation solutions for electronic devices, industrial machinery, and automotive systems.
2. Energy Efficiency: Improved thermal management techniques contribute to enhanced energy efficiency in various systems and devices. By optimizing airflow patterns and heat transfer mechanisms, energy consumption can be minimized, leading to reduced operational costs and environmental impact.
3. Electronics Cooling: In the realm of electronics cooling, the insights obtained from this study can guide the development of better cooling solutions for electronic components and circuitry. Enhanced cooling techniques are crucial for maintaining optimal operating temperatures and prolonging the lifespan of electronic devices.
4. Aerospace and Defense: The findings of this research have implications for aerospace and defense applications, where thermal management is critical for the performance and reliability of aircraft, spacecraft, and military equipment. By understanding how airflow and heat transfer affect temperature regulation, engineers can design more robust thermal control systems for these applications.

V.FUTURE ASPECTS

In anticipation of future experiments, our setup allows for the integration of additional sensors above the plate, enabling the collection of more comprehensive data. Furthermore, the potential inclusion of more precise sensors capable of providing rapid readings could enhance the accuracy and resolution of our measurements. Improvements in insulation could also be implemented to further optimize the thermal performance of the setup.

Additionally, future iterations could explore the possibility of distributing the flow more evenly across the breadth of the plate, potentially improving the uniformity of cooling. Further investigations could involve studying the system's behavior under steady-state conditions with the heater operational, ensuring a balance between energy input and output.

Moreover, there exists the opportunity to explore various calculations and analyses utilizing the collected data. While we attempted one such analysis, time constraints prevented a thorough assessment of its accuracy. Future work could involve validating and expanding upon these calculations to gain deeper insights into the system's behavior and performance.

IV.CONCLUSION

In conclusion, our experiment aimed to investigate the effectiveness of convective air flow in a thermal management system, with a focus on cooling a centrally located heat plate. Through meticulous experimentation and analysis, we have gained valuable insights into the behavior of the system under various conditions.

The results obtained from our study reveal the significant impact of airflow velocity, flap position, and initial temperature on the cooling efficiency of the heat plate. We observed that increasing airflow velocity and optimizing the airflow direction by adjusting the flap position led to enhanced cooling rates and improved thermal regulation.

Furthermore, our analysis of the energy balance and heat transfer coefficient provided valuable theoretical insights into the mechanisms governing heat transfer within the system. While discrepancies between theoretical predictions and experimental observations were noted, these findings underscore the importance of further refinement and validation of theoretical models.

Overall, our study contributes to the body of knowledge on thermal management systems and offers practical insights for engineers and designers seeking to optimize heat dissipation solutions in various applications. By understanding the interplay between airflow dynamics, heat transfer mechanisms, and system parameters, we can develop more efficient and reliable thermal management systems capable of meeting the demands of modern industries.

As we look towards the future, there are ample opportunities for further research and development in this field. By leveraging advanced sensor technologies, improving insulation materials, and exploring novel cooling techniques, we can continue to advance the state-of-the-art in thermal management and contribute to the sustainable development of energy-efficient technologies

V.ACKNOWLEDGMENT

I would like to express my sincere gratitude to Professor Dilip Srinivas Sundaram for his invaluable guidance, unwavering support, and insightful feedback throughout the duration of this research project. His expertise, encouragement, and mentorship have been instrumental in shaping the direction and outcomes of this study.

I am also deeply thankful to Dr. Uddipta Ghosh for his expert advice, valuable suggestions, and continuous encouragement during the course of this research. His expertise in the field of thermal management has been immensely beneficial in navigating through the complexities of the study.

I extend my appreciation to our dedicated teaching assistant, Inzamam Ahmad, for his tireless assistance, timely feedback, and invaluable contributions to this project. His technical expertise, patience, and willingness to help have been invaluable assets throughout the research process.

Special thanks are due to Inzamam Ahmad for providing the heater plate used in the experimental setup and for his assistance with various calculations. His support and assistance have been indispensable in ensuring the smooth execution of the experiments and the analysis of results.

I am grateful to all individuals who have contributed to this research endeavor, directly or indirectly, and whose support has been indispensable in bringing this project to fruition.

VI.REFERENCE

[1]Incropera, F. P., & DeWitt, D. P. (2002). Fundamentals of Heat and Mass Transfer (7th Edition). Retrieved from https://mech.at.ua/HeatandMassTransfer7thEdition-Incropera-dewitt.pdf

[2] IRC, University of Wisconsin-Madison. (n.d.). IRC Database: Properties of Fluids and Solids. Retrieved from https://irc.wisc.edu/properties/

VII.APPENDIX

Appendix A : Raw Data collected
Reading-1 link
Reading-2 link
Reading-3 link
Reading-4 link
Reading-5 link

Appendix B : Code for the plots
Colab file link

Appendix C : Video demonstration of the setup
Youtube link