EVAPORATIVE COOLING

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1. Introduction

Evaporative cooling is a natural process in which water absorbs heat from a surface as it changes its phase from liquid to vapour. Like sweating, it is a phase-change process wherein the water draws energy from its surroundings and thereby causes a cooling effect on the surface. Water evaporating from a heated surface absorbs the surface's heat energy; thus, the temperature drops.
Evaporating cooling has many applications in real life, such as providing cool air to industrial space, and is commonly used for cooling purposes in buildings with large surface areas. It is also used in manufacturing industries as they require cooling because of the heat produced by the equipment.
In this project, we aim to experiment to demonstrate the evaporative cooling on a copper plate. The experimental setup uses a flexible heating strip to control the surface temperatures with controlled water dripping. We will experiment with various environmental conditions, such as different fan speeds and power used to heat the copper plate, to assess their impact on evaporation rates and the overall effect on cooling. Through careful observations and analyses, we aim to demonstrate how evaporation varies with different environmental conditions, along with some insightful results from the experiment.

2. Problem Statement

We aim to demonstrate the extent of cooling that can be achieved through evaporative cooling. The experimental setup consists of a flexible heating strip, a copper surface plate, a controlled water-dripping bag, and a variable-speed fan to assess the correlation among surface temperature, evaporation rates, and cooling efficiency across varying operational conditions. Here are the following measurements that we have aimed to demonstrate.

1. Measure the surface temperature variation with time of a copper plate with dimensions 2.5 cm × 2.5 cm × 2 mm during evaporative cooling.

2. Varying Fan speeds and power to demonstrate the extent of evaporating cooling in different conditions.

3. Temperature drop (T_{drop}) from the original steady state, Cooling response time (t_{res}) to achieve a new steady state, and Temperature recovery time (t_{rec}) after shutting the water drip in different conditions mentioned above.

4. The evaporation rate as a function of temperature and comparison with Cuo plate surface.

3. Governing Equations and Methodology

At steady-state conditions, we assume that input power given to the copper plate is conducted without any loss, and only a fraction of this heat is used by the water droplets on the copper plate to evaporate. Rest of the heat is lost to the surroundings. The energy balance can be depicted as:

$$P_{\text{in}} = Q_{\text{evaporation}} + Q_{\text{loss}} \tag{1}$$

where:

- P_{in}: Heat supplied by the heating strip (W),
- Q_{evap}: Heat lost due to water evaporation (W),
- Q_{loss}: Heat lost to the surroundings (W).

3.1. Heat Input

The heat supplied by the heating strip is given by:

$$Q_{\text{in}} = \frac{V^2}{R}, \tag{2}$$

where:

- V: Voltage applied across the heating strip (V),
- R: Electrical resistance of the heating strip (Ω).

3.2. Evap Heat Loss

The heat loss due to evaporation is calculated as:

$$Q_{\text{evap}} = \dot{m} h_{\text{fg}}, \tag{3}$$

where:

- $\dot{m}$: Mass rate of water evaporation (kg/s),
- h_{fg}: Latent heat of vaporization (J/kg), approximated as:

$$h_{\text{fg}} \approx 2257 - 2.3\,(T_s - 273.15)\ \text{(kJ/kg)}, \tag{4}$$

with T_s as the surface temperature of the copper plate (K).

3.3. Energy Balance

At steady-state, the energy balance simplifies to:

$$P_{\text{in}} = Q_{\text{evap}} + Q_{\text{loss}}. \tag{5}$$

If all terms are known, the heat loss from evaporation can be explicitly calculated as:

$$Q_{\text{evap}} = \dot{m} h_{\text{fg}} \tag{6}$$

3.4. Cooling Efficiency

The efficiency of the evaporative cooling process is defined as:

$$\eta = \frac{Q_{\text{evap}}}{P_{\text{in}}}, \tag{7}$$

where η represents the fraction of supplied heat utilized in evaporation.

3.5. Experimental Steps for Validation

1. Measure the input power Q_{in} using the applied voltage V and resistance R.
2. Determine the mass rate of evaporation $\dot{m}$ from the water dripping mechanism.
3. Calculate $Q_{\text{evaporation}}$ using the mass flow rate and material properties.
4. Verify the energy balance at steady state:

$$P_{\text{in}} \approx Q_{\text{evap}} + Q_{\text{loss}}.$$

3.6. Parameters Involved

Below is a summary of the key parameters involved in the experiment:

Table 1. *Parameters and Units*

Symbol	Description	Unit
P_{in}	Heat supplied by heating strip	W
Q_{evap}	Heat lost by evaporation	W
V	Voltage across heating strip	V
R	Resistance of heating strip	Ω
$\dot{m}$	Mass rate of evaporation	kg/s
h_{fg}	Latent heat of vaporization	kJ/kg
T_s	Surface temperature of copper	K
T_∞	Ambient air temperature	K
A	Surface area of copper plate	m^2
η	Cooling efficiency	-

4. Experimental Setup

The setup for this experiment consists of the following components:

- **Power Source:** A DC power source
- **Silicon Heating Strip:** The DC silicon strip has a maximum power of 20W and can reach temperatures up to 150°C.
- **Copper Plate:** This has dimensions of $50 \times 50 \times 2$ mm, on which water will be dripped and the temperature will be measured.
- **Water Drip:** This bag has a capacity of up to 1.2L of water and features a variable flow rate.
- **Thermocouple:** Used to measure the temperature of the copper plate surface.
- **Table Fan:** Equipped with 3-speed settings, used to cool the surface of the copper plate.
- **Container:** Used to collect any water that spills down.
- **Chemical Balance:** Used to measure the mass of water that spills.
- **Conducting Tapes:** Used to prevent water from spilling onto the heater.

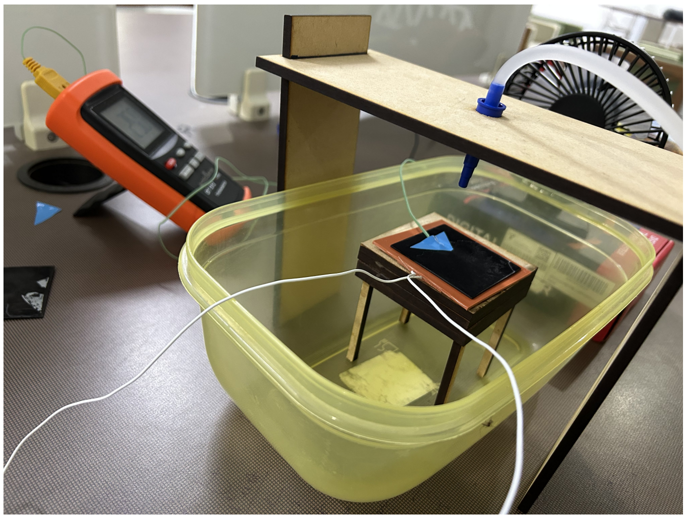

Figure 1. *EXperimental Setup*

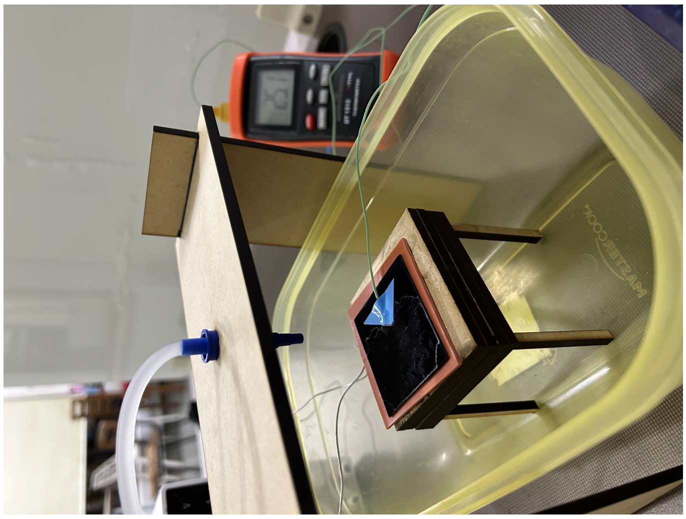

Figure 2. *EXperimental Setup*

5. Experimental Methodology

The experiment can be divided into three stages: Calibration, Establishing Steady State and Measurements

5.1. Calibration

The calibration process is the first stage of the experiment, and it must be performed every time before taking readings. The following steps should be followed:

- Ensure that the copper plate is at a constant room temperature. Once this is achieved, attach the thermocouple to the plate using conducting tape.
- Wipe the container thoroughly to ensure no residual water droplets.
- Fill the dripping bag with exactly 1L of water to maintain a uniform gravitational head. Adjusting the roller allows the water to flow for a given time at a constant rate. Measure the mass of the water by determining the mass difference and dividing it by the density to calculate the volumetric flow rate.

- After determining the flow rate, lock the tube by pressing a clip at the top of the bag. Avoid adjusting the roller further, as it may disturb the flow rate.

Once these conditions are satisfied, start heating the copper plate.

5.2. Achieving Steady State

Heat the copper plate for approximately 30 minutes. The heating duration may vary depending on ambient temperature, fan speed, and heating power. Monitor the readings closely. A steady state is achieved once the readings stabilize, with a variation of less than 2°C/min.

5.3. Measurements

The following steps must be performed once the steady state has been achieved.

- Start the flow of water by unlocking the pipe. The water should only be kept on for a minute. Take note of the initial temperature.
- After stopping the water flow, keep noting the temperature readings at an interval of exactly one minute. Observe the surface of the copper plate to look for water droplets.
- Note the time when the water has been evaporated fully. Wait for a steady state to be achieved.

As soon as a steady state has been achieved, stop the heating and measure the mass of the container to find the amount of water spilt, if any. Let the copper plate cool to room temperature before performing the next experiment.

6. Results

Plot Details:

- **X-axis**: Time elapsed (in minutes).
- **Y-axis**: Temperature readings (in °C) of the copper plate

6.1. Power = 10W, Fan Speed = 1

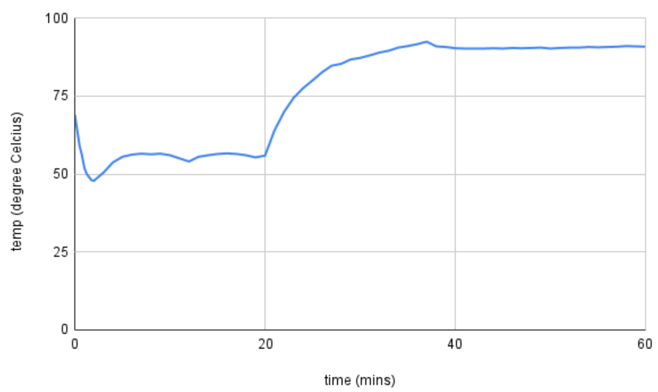

Figure 3. *When P = 10 W, Fan speed = 1*

Rapid Temperature Drop (dripping on) $t = 0$ to 2 minutes $T_{\text{initial}} = 69\,°C$ to $T = 47.8\,°C$
Evaporative Cooling Phase (no water dripping) Lasts till 20 minutes $T = 53\,°C$ (average) $t_{\text{res}} = 2$ minutes
Achieved 3 Steady States **1. Initial State**: $T = 69\,°C$, time = 0 minutes (before water dripping starts) **2. Evaporative Cooling State**: $T = 53\,°C$, at $t = 9$ minutes **3. Final State**: $T = 90\,°C$, time = 40 minutes (after complete water evaporation)
Rate of Evaporation = $0.004\,11\,mL\,s^{-1}$

Table 2. *Results from Plot 1*

6.2. Power = 10W, Fan Speed = 3

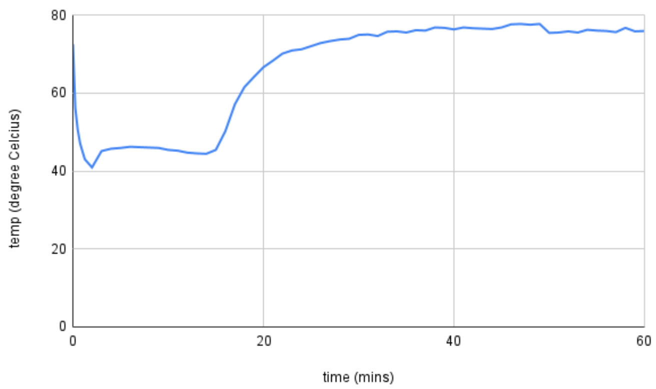

Figure 4. *When P = 10W, Fan speed = 3*

Rapid Temperature Drop (dripping on) $t = 0$ to 2 minutes $T_{\text{initial}} = 72\,°C$ to $T = 40.9\,°C$
Evaporative Cooling Phase (no water dripping) Lasts till 15 minutes $T = 45\,°C$ (average) $t_{\text{res}} = 2$ minutes
Achieved 3 Steady States **1. Initial State**: $T = 72\,°C$, $t = 0$ (before water dripping starts) **2. Evaporative Cooling State**: $T = 45\,°C$, at $t = 6$ minutes **3. Final State**: $T = 75\,°C$, time = 35 minutes (after complete water evaporation)
Rate of Evaporation = $0.0056\,mL\,s^{-1}$

Table 3. *Results from Plot 2*

6.3. Power = 8W, Fan Speed = 1

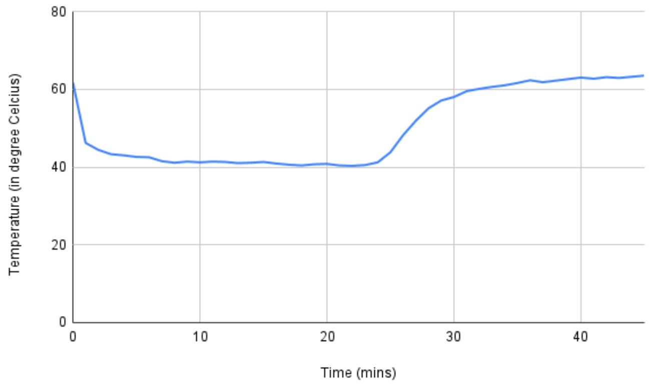

Figure 5. *When P = 8W, Fan Speed = 1*

Rapid Temperature Drop (dripping on) $t = 0$ to 1 minutes $T_{\text{initial}} = 61.7\,°\text{C}$ to $T = 44.4\,°\text{C}$
Evaporative Cooling Phase (no water dripping) Lasts till 24 minutes $T = 40.5\,°\text{C}$ (average) $t_{\text{res}} = 90\,\text{s}$
Achieved 3 Steady States **1. Initial State**: $T = 61.7\,°\text{C}, t = 0$ (before water dripping starts) **2. Evaporative Cooling State**: $T = 45\,°\text{C}$, at $t = 19$ minutes **3. Final State**: $T = 63.5\,°\text{C}$, time = 44 minutes (after complete water evaporation)
Rate of Evaporation = $0.002\,12\,\text{mL}\,\text{s}^{-1}$

Table 4. *Results from Plot 3*

6.4. Power = 8W, Fan Speed = 3

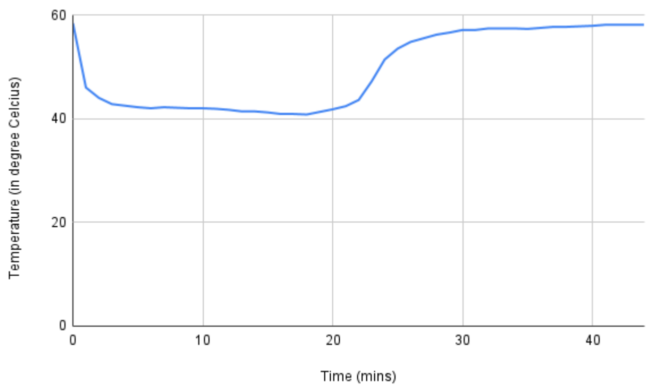

Figure 6. *When P = 8W, Fan Speed = 3*

Rapid Temperature Drop (dripping on) $t = 0$ to 40 seconds $T_{\text{initial}} = 58.4\,°\text{C}$ to $T = 44\,°\text{C}$
Evaporative Cooling Phase (no water dripping) Lasts till 20 minutes $T = 42.5\,°\text{C}$ (average) $t_{\text{res}} = 60\,\text{s}$
Achieved 3 Steady States **1. Initial State**: $T = 58.4\,°\text{C}, t = 0$ (before water dripping starts) **2. Evaporative Cooling State**: $T = 42\,°\text{C}$, at $t = 10$ minutes **3. Final State**: $T = 57.4\,°\text{C}$, time = 35 minutes (after complete water evaporation)
Rate of Evaporation = $0.004\,278\,\text{mL}\,\text{s}^{-1}$

Table 5. *Results from Plot 4*

7. Discussion and Inference

The experimental surface temperature-time curves show three phases:

- Steady-State Phase: Before the water drip began, the copper plate achieved a steady temperature (T_s), determined by the heating power.
- Cooling Phase: When the water dripping is started, it causes the plate's temperature decreases sharply, with the cooling rate influenced by fan speed, initial plate temperature, and dripping rate.
- Recovery Phase: Once the dripping is stopped, the plate's temperature gradually returns to its initial steady-state value.

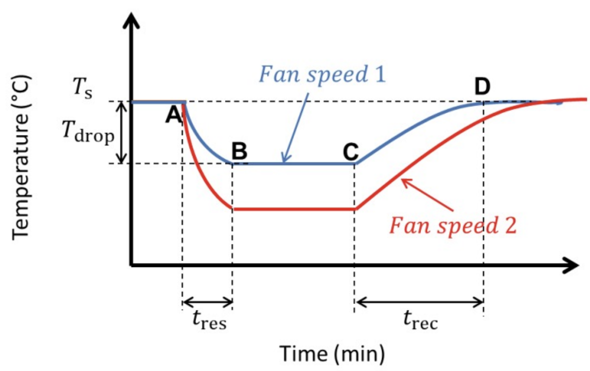

Figure 7. *Temperature-time curve*

7.1. Discussion

7.1.1. Effect of Surface Temperature (T_s). It was observed that higher initial temperatures (due to higher heating power) resulted in greater temperature drops (T_{drop}) because more heat was available for evaporation.

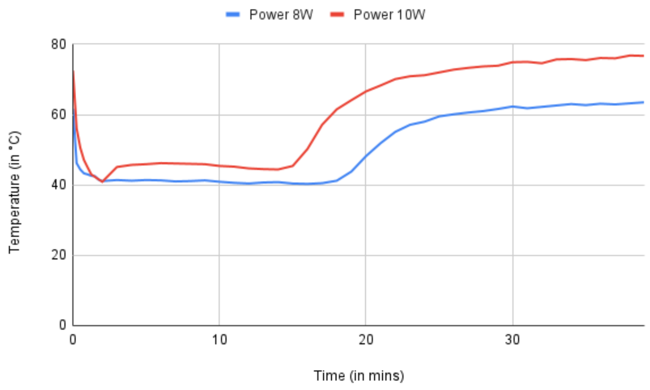

Figure 8. *When P = 8W and 10W, Fan Speed = 1*

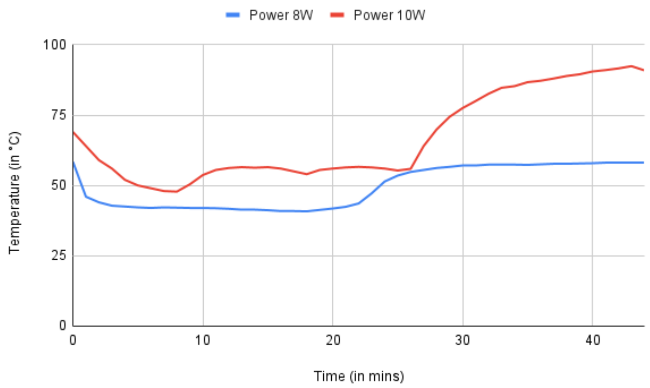

Figure 9. *When P = 8W and 10W, Fan Speed = 3*

The higher temperatures enhance the evaporation rate due to higher thermal energy at the surface. The steady-state temperature achieved during the cooling phase depends on the heat supplied by the heating pad and the heat removal rate by evaporation.

At 10 W with fan speed 1, the evaporation rate was 0.00411 mL/s. At 8 W, this rate was 0.00212 mL/s. At fan speed 3, the evaporation rate was 0.00556 ml/s for power 10 W and 0.00427 ml/s for power 8. It is observed that when higher heating power is supplied, the evaporation rate is enhanced.

Power	Initial Temperature	Temperature Drop
8 W	69°C	16°C
10 W	72°C	27°C

Table 6. *Temperature drop when fan speed = 1*

Power	Initial Temperature	Temperature Drop
8 W	61.7°C	21.2°C
10 W	58.4°C	15.9°C

Table 7. *Temperature drop when fan speed = 3*

7.1.2. Effect of Fan Speed. Forced convection enhanced the evaporation rate by reducing the boundary layer of vapour above the plate. This caused faster cooling and reduced response time. The fan also contributed to faster recovery times (t_rec) by dissipating heat more efficiently during recovery.

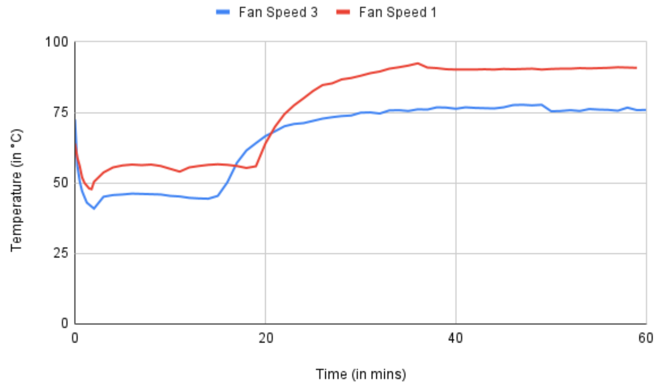

Figure 10. *When P = 10W, Fan Speed = 1 and 3*

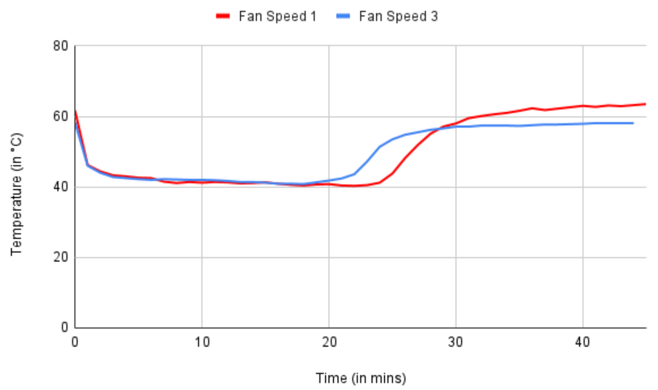

Figure 11. *When P = 8W, Fan Speed = 1 and 3*

Fan speed affects the convective heat transfer from the copper plate. When the fan speed was increased to 3, a significant increase in evaporation rate was observed, especially at 10 W power. This demonstrates that higher fan speeds enhance evaporation by improving the cooling effect and increasing heat dissipation.

Fan Speed	t_{rec} (in min)
1	44
3	35

Table 8. *Power = 8W*

Fan Speed	t_{rec} (in min)
1	40
3	35

Table 9. *Power = 10W*

7.2. Sample Calculations

The following is a step-by-step sample calculation for determining the efficiency of the system:

1. **Given:**

- Input Power: $P_{\text{in}} = 8\,\text{W}$
- Rate of Evaporation: $0.00212\,\text{mL/s}$
- Mass Flow Rate:
$$\dot{m} = 2.12 \times 10^{-6}\ \text{kg/s}$$
- Latent Heat of Vaporization of Water:
$$h_{\text{fg}} = 2.257 \times 10^{6}\ \text{J/kg}$$

2. **Calculation of Heat Energy for Evaporation:**
$$\dot{Q}_{\text{evap}} = \dot{m} \cdot h_{\text{fg}} = 2.12 \times 10^{-6} \cdot 2.257 \times 10^{6}\ \text{J/s} = 4.78\,\text{W}$$
3. **Using Energy Balance:**
$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{evap}} + \dot{Q}_{\text{loss}}$$
Rearranging for $\dot{Q}_{\text{loss}}$:
$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{evap}} = 8\,\text{W} - 4.78\,\text{W} = 3.22\,\text{W}$$
The energy balance is thus satisfied.
4. **Calculation of Efficiency (η):**
$$\eta = \frac{\dot{Q}_{\text{evap}}}{P_{\text{in}}} \times 100 = \frac{4.78}{8} \times 100 = 59.75\%$$
This indicates that about half of the input power is used by the water droplets to evaporate.

7.3. Inference

- Evaporative cooling effectively reduces surface temperatures, and its efficiency depends on parameters such as fan speed and surface temperature.
- Higher heating power increases the initial surface temperature (T_s), resulting in a greater temperature drop (T_{drop}) enhancing evaporation rates, and thus cooling efficiency.
- A higher fan speed improves cooling by increasing evaporation rates and reducing the cooling response time (t_{res}).
- during the recovery phase, Forced Convection helps faster recovery by improving heat dissipation and thus enhancing the evaporating rates.

8. Conclusions

- The experiment demonstrated the potential of evaporative cooling as a practical and efficient cooling technique. Significant temperature drops were observed when water was introduced.
- Higher heating power resulted in greater initial temperatures and subsequently more significant temperature drops (Tdrop). This shows that the heat on the surface directly influences the effectiveness of the cooling process by providing more thermal energy for evaporation.
- Increased fan speed enhanced the evaporation rate significantly and promoted faster heat dissipation. This effect was especially seen during the cooling phase. Increased fan speed also accelerated recovery time for the surface to return to its original steady-state temperature.
- Therefore, by systematically varying heating power and external airflow conditions, we can identify that higher fan speeds combined with higher heating power provide the most effective cooling performance.

9. Novelty

We had to use a copper strip as stated in our problem statement. Apart from this, we also used prepared a CuO strip and took additional readings which are shown below:

9.1. Power = 8W, Fan Speed = 1

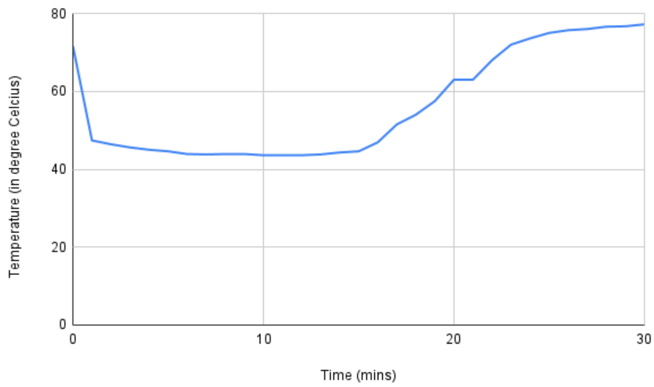

Figure 12. *For CuO (Power = 8W), (Fan Speed = 1)*

We can infer the following from the Figure 12:

- **Initial drop:** The temperature drops rapidly from 0->1 minute when we turn the dripping on.
$T_{\text{initial}} = 71.6\,°\text{C}$ to $T = 46.4\,°\text{C}$
- **Evaporative Cooling Phase:** It starts when we stop the water dripping. It lasts for 15 minutes.
Achieves an average temperature of $T = 43.9\,°\text{C}$
$t_{\text{res}} = 90\text{s}$
- **Temperature Increase:** The temperature increase is due to the complete evaporation of water.
- **Steady State:** Finally, it achieves a steady state at $T = 76.7\,°\text{C}$ after 13 minutes.

The rate of evaporation was found out to be $0.00169\ \text{mLs}^{-1}$.

9.2. Power = 8W, Fan Speed = 3

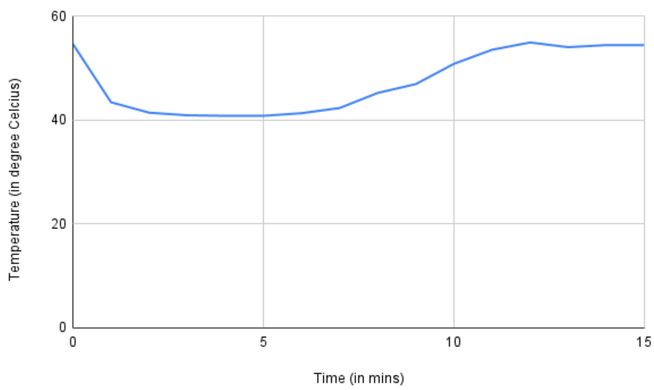

Figure 13. *For CuO (Power = 8W), (Fan Speed = 3)*

We can infer the following from the Figure 13:

- **Initial drop:** The temperature drops rapidly from 0->20s when we turn the dripping on.
  $T_{initial} = 54.6\,°C$ to $T = 41.4\,°C$
- **Evaporative Cooling Phase:** It starts when we stop the water dripping. It lasts for 5 minutes.
  Achieves an average temperature of $T = 41\,°C$
  $t_{res} = 50s$
- **Temperature Increase:** The temperature increase is due to the complete evaporation of water.
- **Steady State:** Finally, it achieves a steady state at $T = 76.7\,°C$ after 13 minutes.

The rate of evaporation was found out to be 0.00113 mLs^{-1}.

9.3. Conclusion

- Since the CuO is non-conducting the evaporation rate is much less than compared to Cu plate.
- The CuO plate being hydrophilic can also be one of the reasons that we are getting low values of evaporation rate as compared to Copper plate.

10. Critical analysis and challenges faced

While conducting the experiment, several challenges arose, which are listed as follows:

1. **Water Runoff :** While experimenting, we saw that the smooth surface of the copper plate caused water to run off, which made it very difficult for us to proceed as planned. It was important for the water to stay stable on the plate for the experiment to work properly. To solve this issue, we adjusted the setup by adding some height to the table, which helped prevent the water from running off.
2. **Heating Strip :** Since the heating strips were made of electrical heating elements, we had to be very careful to avoid water droplets getting inside them, as this could jeopardize the entire experiment. We brainstormed different ideas to solve this issue. Initially, we considered making a case to cover the heating strip and copper plate to stop water from entering. However, this didn't work because the material for the case needed to withstand the high heat from the heating strip, which was hard to find. Finally, we used conducting tape to seal the gap between the copper plate and the heating strip, which solved the problem.
3. **Constant Temperature Readings :** We had trouble maintaining a constant temperature for our readings during the experiment. A steady surrounding temperature was necessary to achieve a fixed steady state, but the temperature outside kept fluctuating between day and night. This made it difficult to keep the temperature stable. To solve this, we moved our setup to the AB-6 workspace, which provided a more controlled environment and allowed us to get consistent temperature readings.
4. **Switching to Dripping Bag for Improved Coverage :** We initially used a syringe to drip water. However, the water droplets covered only a small surface area, limiting the process's effectiveness. On suggestion, we switched to a dripping bag. This adjustment allowed the water to cover a larger surface area, improving the overall efficiency and accuracy of the experiment.
5. **Optimizing Reading Intervals for Efficiency :** At the start, we took each reading at intervals of 10 seconds, but this approach proved extremely tedious and required constant, undivided attention. To make the process more manageable and efficient, we took readings at 1-minute intervals. This adjustment allowed us to focus better while still maintaining the accuracy of the experiment.
6. **Ensuring Temperature Stabilization for Accurate Measurements :** The temperature rose significantly during the experiment. To ensure accurate readings, after recording one set of data (e.g., keeping the flow rate constant and varying other parameters), we had to wait for the system to stabilize and the temperature to return to a steady state before proceeding to the next measurement. This step was crucial for maintaining consistency and reliability in the results and consumed much time.

11. Future Work

The following improvements and additions can be considered to enhance the experiment:

- **Flow Rate Control:** Incorporating precise control over the flow rate would allow for better analysis and comparison between different experimental cases.
- **Wetted Area Measurement:** By utilizing computer vision techniques, the wetted area of the copper surface can be measured as a function of time, providing valuable insights into wetting dynamics.
- **Use of Porous CuO:** The experiment can be conducted using porous CuO, which may offer unique heat transfer and wetting properties for further study.

12. Contribution

Aarav Shah

The contributions made by the group leader to this report are as follows:

- As the group leader, managed the work distribution, coordinated with team members for smooth collaboration, and ensured the project was completed on time.
- Actively contributed during the ideation phase of the experiment, helping in brainstorming and formulating the experimental objectives and design.
- Played a significant role in the fabrication of the experimental setup.
- Conducted the actual experiments on both copper and CuO samples.
- Authored the sections on *Experimental Methodology* and *Experimental Setup* in the report, providing clear and concise documentation of the procedures and experimental details.

Diya Mehta

I worked on the ideation of the experimental setup, taken readings worth 10 hours, helped in video editing, written the discussion and inference section.

Mihika

I was a part of ideation of the setup and the planning part of how we would proceed with the setup. For the final phase, I was responsible for recording initial readings at a power of 10 W with fan speeds 1 and 3. I contributed to the results section by plotting Temperature vs. Time graphs, calculating evaporation rates for varying power supplies (10W and 8W) and fan speeds (1 and 3), and analyzing results for Copper Oxide (at 8W power and fan speeds 1 and 3). Additionally, I derived and documented key metrics such as t_{res} and t_{rec}, along with other analysis mentioned around the results facilitating deeper insights into the experiment.

Archit

1. Contributed to the experiment's ideation and setup design in TL and took readings from the experiment worth 10 hours.
2. Helped in constructing the setup from scratch.
3. Tasked with writing the introduction and problem statement in the report.

Vidhi

I actively contributed to the initial discussions for planning and defining the project setup, I had a hand in the experiment by taking a necessary reading like fan speed equal to 1 and voltage equal to 8V. I also worked on the first derivations to provide a theoretical framework for the project, then refined it by adhering to the feedback we got from phase 1 report and then redefined the governing equations necessary for the experiment.

Nimesh Goyal

1. Actively took part in discussions and was responsible with coming up with ideas for building the experimental setup.
2. Helped in constructing the setup from scratch.
3. Tackled and resolved some of the challenges, which I have detailed in the "Problems Faced" section of the report.
4. Ensured that the setup was fully operational and ready for testing.
5. Took various readings of the setup for Copper strip and CuO plate.
6. Responsible for adding the Novelty and Critical Analysis section of the report.

Shrishti

1. Contributed to the ideation of the experiment and took readings worth 10 hours, helped in recording video in the first part.
2. Tasked with writing problem faced during the experiment section of the report.

Vatsal

1. Contributed in setting up the experiment and took readings worth of 4-5 hours.
2. Derived Conclusions in the report.

Shivaprakash

13. References

References

[1] F. Incropera, D. DeWitt, T. Bergman, and A. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th ed., Wiley, 2007.