Evaporative Cooling (Phase-1 Report)

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1. Problem Statement

This project investigates the cooling effect achieved through evaporative cooling on a copper plate under controlled experimental conditions.

The experimental setup will utilize a flexible heating strip to maintain a consistent surface temperature, while a continuous dripping mechanism will introduce water at a predetermined rate.

The impact of ambient conditions, specifically varying fan speeds and the resulting airflow patterns, will also be examined to assess their influence on the rate of evaporation and, consequently, the cooling efficiency.

By meticulously measuring surface temperatures over time and analyzing the thermal response under varying conditions, the project will identify the optimal configurations for maximizing evaporative cooling efficiency.

The expected outcomes include:

1. Characterization of the cooling curves under different experimental conditions.
2. Quantification of key metrics such as temperature drop (T_{drop}), cooling response time (t_{res}), and temperature recovery time (t_{rec}).
3. An assessment of the rate ofevaporation rateunction of temperature, fan speed, and water dripping rate.

2. Apparatus

The design of the apparatus will be as follows:

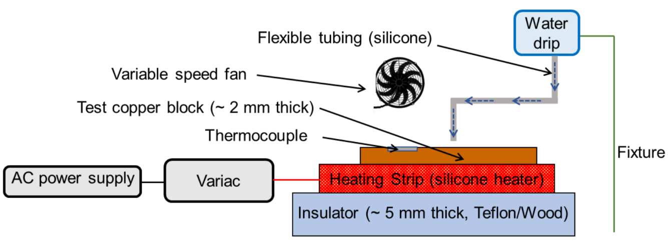

Figure 1. *Proposed Design*

Components

The following components were primarily used:

- **25mm × 25mm × 2mm Copper Plate**: Acts as the primary surface for the experiment.
- **3-Speed Table Fan**: Used to control the airflow over the copper plate.
- **Silicone Heating Strip**: Applied to heat the copper plate.
- **Thermocouples**: Employed to measure the temperature of the copper plate.
- **Water Dripping Bag**: Provides a controlled, drop-by-drop flow of water onto the copper plate.
- **Variac**: Used to adjust the power supplied to the heating strip.

3. Theory

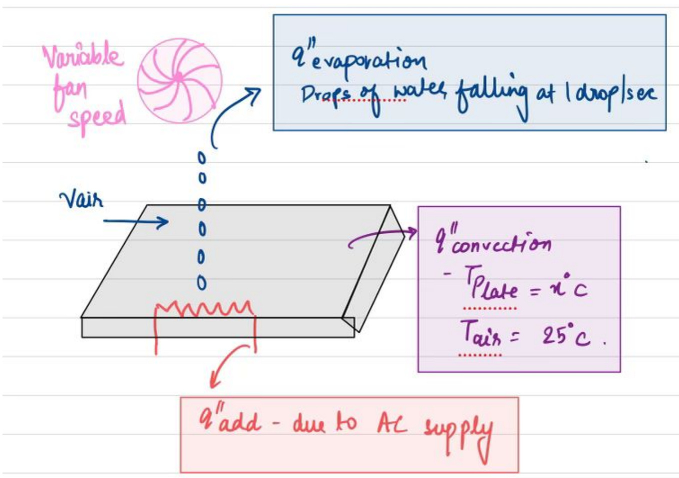

Figure 2. *Using Energy Conservation*

Evaporative cooling is a natural phenomenon that occuruid, typically water, absorbs heat from its surroundings as it transitions from a liquid state to vapor.

The core of evaporative cooling lies in the phase change of water. When water evaporates, it requires energy, known as the latent heat of vaporization. This energy is taken from the surrounding environment, leading to a decrease in the temperature of the surface from which the water evaporates. When evaporative cooling is applied to a heated surface, the temperature of that surface begins to drop as the water evaporates. This process can be broken down into distinct phases:

1. Heating Phase: Initially, the heater is activated, and the copper plate reaches a steady-state temperature. This is the baseline temperature before any cooling occurs.

2. Evaporation Phase: Once water is introduced, it begins to absorb heat from the copper plate, causing the plate's temperature to decrease. The rate of heat loss during this phase is governed by the rate of water flow and the conditions surrounding the copper plate.

3. Recovery Phase: After the water supply is stopped, the plate will continue to lose heat until it returns to the original steady-state temperature. This recovery phase is crucial for understanding the thermal dynamics of the system.

In addition to evaporative heat loss, convective heat transfer plays a significant role in the cooling process. The convective heat transfer coefficient quantifies how effectively heat is transferred from the surface to the surrounding air. It is influenced by factors such as air velocity, temperature differences, and surface roughness.

Consider a copper plate with the following dimensions:

- Length: L
- Width: W
- Thickness: t

Input parameters:

- Voltage: V
- Current: I

Water droplet information:

- Droplet rate: f (drops per second)

Environmental conditions:

- Ambient temperature: T_{air}
- Initial temperature of the plate: T_s
- Air velocity: v_{air}

Fluid properties:

- Kinematic viscosity of air: ν
- Thermal conductivity of air: k_{air}
- Prandtl number: Pr

Thermodynamic property:

- Latent heat of vaporization of water: h_{fg}

The heat loss from the system can be represented as:

$$Q_{\text{loss}} = Q_{\text{evap}} + Q_{\text{conv}}$$

where:

- Q_{evap} is the energy lost due to evaporation.
- Q_{conv} is the energy lost due to convection.

For evaporation, the energy loss is given by:

$$Q_{\text{evap}} = m_{\text{water}} \cdot h_{fg}$$

where:

- $m_{\text{water}} = f \cdot \rho \cdot V_{\text{drop}}$ is the mass of the evaporated water.
- f is the droplet rate (drops per second).
- ρ is the density of water.
- V_{drop} is the volume of each water droplet.
- h_{fg} is the latent heat of vaporization.

For convection, the energy loss is calculated using:

$$Q_{\text{conv}} = h_{\text{conv}} \cdot A \cdot (T_s - T_{\text{air}})$$

where:

- h_{conv} is the convective heat transfer coefficient.
- A is the surface area of the plate.
- T_s is the surface temperature of the plate.
- T_{air} is the ambient air temperature.

The convective heat transfer coefficient h_{conv} is given by:

$$h_{\text{conv}} = \frac{\text{Nu} \cdot k_{\text{air}}}{L}$$

where:

- Nu is the Nusselt number.
- k_{air} is the thermal conductivity of air.
- L is the characteristic length of the plate.

The Nusselt number Nu can be calculated using:

$$\text{Nu} = 0.664 \cdot \text{Re}^{0.5} \cdot \text{Pr}^{1/3}$$

where:

- Re is the Reynolds number, given by $\text{Re} = \frac{v_{\text{air}} \cdot L}{\nu}$, where v_{air} is the velocity of air and ν is the kinematic viscosity of air.
- Pr is the Prandtl number.

Considering the external energy supply, the energy provided is:

$$Q_{\text{ext}} = V \cdot I$$

Using the energy balance equation, we can conclude:

$$Q_{\text{loss}} = Q_{\text{ext}}$$

4. Theoretical Calculations

1. Evaporative Heat Loss ($Q_{\text{evaporation}}$)

The heat loss due to the evaporation of water droplets is calculated as:

$$Q_{\text{evaporation}} = \dot{m}_{\text{water}} \times h_{\text{fg}}$$

$$Q_{\text{evaporation}} = 5 \times 10^{-5} \times 2257 \times 10^{3} = 112.85\,\text{W}$$

The efficiency of evaporative cooling is influenced by the rate of evaporation, which is dependent on several factors, including temperature, humidity, air velocity, and surface area.

2. Convective Heat Loss ($Q_{\text{convection}}$)

The convective heat transfer depends on the air velocity and the properties of the air. We start by calculating the Reynolds number (Re):

$$Re = \frac{v_{\text{air}} \times L}{\nu} = \frac{2 \times 0.025}{16.5 \times 10^{-6}} \approx 3030$$

Since $Re < 5 \times 10^{5}$, the flow is laminar.

Next, the Nusselt number (Nu) is calculated using the empirical correlation for laminar flow:

$$Nu = 0.664 \times Re^{0.5} \times Pr^{1/3}$$

$$Nu = 0.664 \times (3030)^{0.5} \times (0.7)^{1/3} \approx 32.36$$

The convective heat transfer coefficient (h_{conv}) is then:

$$h_{\text{conv}} = \frac{Nu \times k_{\text{air}}}{L} = \frac{32.36 \times 0.026}{0.025} \approx 33.64\,\text{W/m}^2{\cdot}\text{K}$$

The convective heat loss is:

$$Q_{\text{convection}} = h_{\text{conv}} \times A \times (T_{\text{plate}} - T_{\text{air}})$$

$$Q_{\text{convection}} = 33.64 \times 6.25 \times 10^{-4} \times (50 - 25) = 0.53\,\text{W}$$

3. Total Heat Loss (Q_{loss})

The total heat loss is the sum of the evaporative and convective heat losses:

$$Q_{\text{loss}} = Q_{\text{evaporation}} + Q_{\text{convection}} = 112.85 + 0.53 = 113.38\,\text{W}$$

4. Energy Balance

At steady state, the input power should equal the heat losses:

$$Q_{\text{input}} = Q_{\text{loss}}$$

$$24\,\text{W} \neq 113.38\,\text{W}$$

This imbalance suggests that our assumptions need to be adjusted.

5. Adjusting Water Droplet Parameters

We reduce the water drop volume to 0.01 mL (1×10^{-8} m^3). The new mass per drop is:

$$m_{\text{drop}} = \rho_{\text{water}} \times V_{\text{drop}} = 1000 \times 1 \times 10^{-8} = 1 \times 10^{-5}\,\text{kg}$$

The new mass flow rate is:

$$\dot{m}_{\text{water}} = m_{\text{drop}} \times f = 1 \times 10^{-5} \times 1 = 1 \times 10^{-5}\,\text{kg/s}$$

The new evaporative heat loss is:

$$Q_{\text{evaporation}} = 1 \times 10^{-5} \times 2257 \times 10^{3} = 22.57\,\text{W}$$

6. Recalculate Total Heat Loss

The new total heat loss is:

$$Q_{\text{loss}} = Q_{\text{evaporation}} + Q_{\text{convection}} = 22.57 + 0.53 = 23.10\,\text{W}$$

7. Energy Balance

Now:

$$Q_{\text{input}} = 24\,\text{W}$$

$$Q_{\text{loss}} = 23.10\,\text{W}$$

The heat input and loss are closely matched, allowing us to proceed with estimating the steady-state plate temperature.

8. Steady-State Plate Temperature (T_{plate})

Using the energy balance:

$$Q_{\text{input}} = Q_{\text{evaporation}} + h_{\text{conv}} \times A \times (T_{\text{plate}} - T_{\text{air}})$$

$$24 = 22.57 + 33.64 \times 6.25 \times 10^{-4} \times (T_{\text{plate}} - 25)$$

$$24 - 22.57 = 0.021 \times (T_{\text{plate}} - 25)$$

$$1.43 = 0.021 \times (T_{\text{plate}} - 25)$$

Solving for T_{plate}:

$$T_{\text{plate}} = 25 + \frac{1.43}{0.021} \approx 93.1^\circ\,\text{C}$$

9. Final Convective Heat Loss

At $T_{\text{plate}} = 93.1^\circ$C, the convective heat loss is recalculated as:

$$Q_{\text{convection}} = 33.64 \times 6.25 \times 10^{-4} \times (93.1 - 25) \approx 1.43\,\text{W}$$

10. Energy Balance Verification

The updated total heat loss is:

$$Q_{\text{loss}} = 22.57 + 1.43 = 24\,\text{W}$$

Thus, $Q_{\text{input}} = Q_{\text{loss}}$, confirming the steady-state plate temperature of approximately 93.1°C.

11. Summary

- **Steady-State Plate Temperature:** 93.1°C
- **Evaporative Heat Loss:** 22.57 W
- **Convective Heat Loss:** 1.43 W
- **Total Heat Loss:** 24 W
- **Energy Balance Achieved:** Yes

5. Experimental Procedure

1. **Setup Preparation**
   (a) Place the copper plate (2.5 cm x 2.5 cm, 2 mm thickness) on top of a Teflon plate to minimize heat loss to surroundings.
   (b) Attach the silicone flexible heater to the underside of the copper plate, ensuring good thermal contact. Apply thermal paste if necessary to ensure uniform heating.

(c) Connect the heater to the power supply through the Variac. Ensure all electrical connections are secure.

(d) Attach a thermocouple to the top surface of the copper plate to measure its surface temperature. Ensure that the thermocouple is placed at the center of the plate for accurate readings.

(e) Position the water drip system above the copper plate. Adjust the flow rate to approximately 1 drop per second initially.

(f) Place an external fan directed at the copper plate, ensuring that the airflow can be varied (off, low, medium, high).

2. **Initial Heating**

   (a) Turn on the Variac and set it to a low power setting to start heating the copper plate.

   (b) Monitor the temperature using the thermocouple until the temperature reaches a steady state. This is the dry surface temperature of the copper plate.

   (c) Record this steady-state temperature as the initial temperature T_s.

3. **Evaporation and Cooling Process**

   (a) Once the dry steady-state temperature is attained, start the water drip system and ensure that the copper plate is uniformly wetted.

   (b) Observe and record the temperature drop over time as the water evaporates from the copper plate surface.

   (c) Vary the fan speed (off, low, medium, high) to study the effect of airflow on the rate of evaporation and cooling.

   (d) Allow the system to reach a new steady-state temperature while the plate remains wet. Record this temperature as T_{wet}.

4. **Stopping the Water Drip**

   (a) Once the steady-state wet temperature is reached, stop the water drip system.

   (b) Observe the temperature of the copper plate as it starts to rise and eventually returns to its initial dry steady-state temperature.

   (c) Record the recovery time t_{rec} and the final temperature.

5. **Repeat the Experiment**

   (a) Repeat the experiment for three different surface temperatures by adjusting the Variac power setting.

   (b) Vary the water drip rate (e.g., 0.5 drops/sec, 1 drop/sec, 2 drops/sec) and repeat the procedure to study its effect on cooling.

   (c) Record data for three different fan speeds to analyze the impact of airflow on the rate of evaporation and cooling efficiency.

6. **Data Analysis**

   (a) Plot the surface temperature versus time curves for the different fan speeds, surface temperatures, and water drip rates.

   (b) Calculate the temperature drop T_{drop}, cooling response time t_{res}, and temperature recovery time t_{rec} for each case.

   (c) Determine the rate of evaporation as a function of surface temperature and analyze the effect of fan speed and water drip rate on the evaporation process.

6. Recommendations for Experimental Setup

- Control water droplet size and rate to ensure accurate heat transfer calculations.
- Use a precise thermocouple to monitor plate temperature.
- Adjust fan speed to vary convective heat transfer as necessary.
- Consider radiation heat loss if the plate temperature exceeds 100°C.

7. Expected Results

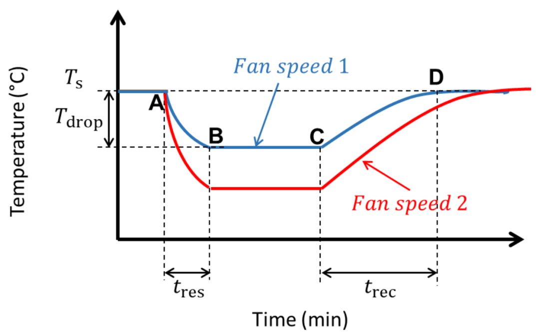

Figure 3. *Expected Results*

7.1. Surface Temperature versus Time Curve

The surface temperature versus time curve for the copper plate needs to be presented for the following conditions:

- **At least 2 different values of T_s (Surface Temperature):**
- **At least 2 different water dripping rates:**
- **At least 3 different fan speeds:** (including no fan/fan off as one of the settings)

7.2. Temperature Drop, Cooling Response Time, and Temperature Recovery Time

For each of the above cases, the following parameters need to be analyzed:

- **Temperature Drop** (T_{drop})
- **Cooling Response Time** (t_{res})
- **Temperature Recovery Time** (t_{rec})

7.3. Rate of Evaporation as a Function of Temperature

The rate of evaporation needs to be studied as a function of temperature.