686 Museum Rd.
Gainesville, FL 32611
16 June 2023

Ryan Rinzel
University of Florida Nuclear Sciences Building
1929 Stadium Rd., Room 0312
Gainesville, FL 32611

Dear Mr. Rinzel,

The objective of this lab is to characterize the performance of a cooling tower; this goal is accomplished via mass and energy balancing equations, employing measured entrance/exit temperature values of both air and water. Air temperature data is used to determine enthalpy, relative humidity, and humidity ratios. As for water temperature data, the entrance and exit temperature measurements are used to calculate heat transfer rate, which aids in determining the cooling tower effectiveness.

Cooling towers utilize evaporating falling liquid to transfer energy into flowing air. The liquid evaporating to vapor is a transfer to a higher energy state, meaning energy is required to break the molecular bonds. This molecular level energy transfer results in reduced enthalpy in the liquid, and increased enthalpy in the air vapor. Cooling towers stimulate advanced evaporation by increasing surface area within the tower by spreading water across thin plates. This experiment assumed no external energy was added to the system once water entered the tower. The experiment and analysis utilized a first law analysis which assumed that mass and energy input to the system was equivalent to the exit mass and energy values.

This experiment utilized an H891 Bench Top Cooling Tower which contained its own closed-loop distilled water system. The water system had three heat input settings, along with a water pump and recollection components. Data was measured using six temperature sensors — four for air data (two dry bulb, two wet bulb) and two for water data. Air was pumped through the cooling tower using a fan, adjusted via an air damper. As water was pumped into the tower, the water was distributed among plates to maximize the surface area of the water exposed to air. This experiment was run at six different configurations which were set before temperature measurement. The controlled parameters were heating power, water mass flow rate, and air pressure drop with air pressure drop remaining constant throughout the experiment. The temperature data, T_1-T_6, were recorded at 20, 30, and 40 g/s water mass flow rate at each of 0.5 kW and 1.5 kW. Closed toed shoes and safety glasses were worn as safety precautions.

To characterize the performance of the cooling tower, measured water temperature at exit and calculated heat dissipation rates, *Q*, were compared to predicted values calculated using a first law analysis. For all six test configurations, the actual water exit temperature was lower than predicted. The difference between predicted and actual water exit temperature was higher at 1.5 kW vs 0.5 kW heating settings. 1.5 kW predictions were an average of 3.7 degrees Kelvin off, and 0.5 kW tests were an average of 2.1 degrees Kelvin off. As for heat dissipation, the higher 1.5 kW heating tests showed higher heat transfer out of the water versus the 0.5 kW setting. All six tests demonstrated higher heat dissipation than predicted, so the opposite relationship was observed at the water exit temperature. The same observation was seen as water temperature when comparing heat dissipation in 0.5 kW versus 1.5 kW tests. 0.5 kW tests saw an average of 0.12 kW difference from predicted, and the 1.5 kW tests saw an average of 0.33 kW difference in predicted vs actual heat dissipation.

Sincerely,

Conor Bowman	alex C.	allison K. Porras	
Conor Bowman	Alex Carr	Allison Porras	David Reyes-Tobar

“On my honor, I have neither given nor received unauthorized aid in doing this assignment.”

Table 1: Air inlet and exit humidity ratios and relative humidities for each test condition. The values were found by interpolating the psychometric chart using dry and wet bulb temperatures. The air inlet temperatures are T_1 and T_2 and the air outlet temperatures are T_3 and T_4.

Test	ω_{in}	ω_{exit}	φ_{in}	φ_{out}
1	0.00647	0.01055	46.90	85.05
2	0.00637	0.01052	46.17	85.89
3	0.00647	0.01063	46.90	86.80
4	0.00643	0.01285	46.31	87.73
5	0.00643	0.01289	46.31	86.94
6	0.00643	0.01285	46.31	87.73

Table 2: Measured and predicted exit temperature and heat transfer rate values for each test condition. The predicted temperature values were calculated using a first law analysis and subsequently compared to the actual data collected during the experiment.

Test	$T_{\text{exit, predicted}}$ **[K]**	$T_{\text{exit, actual}}$ **[K]**	ΔT **[K]**	$Q_{predicted}$ **[kW]**	Q_{actual} **[kW]**	ΔQ **[kW]**
1	291.7	289.0	2.7	0.382	0.543	0.161
2	290.8	288.9	1.9	0.382	0.497	0.115
3	290.6	289.0	1.7	0.382	0.476	0.095
4	295.5	291.8	3.7	0.812	1.079	0.267
5	295.7	291.9	3.9	0.812	1.185	0.372
6	295.1	291.8	3.4	0.812	1.155	0.343

Sample Calculations

First, the humidity ratios of both inlet and exit conditions (ω_1 and ω_2, respectively) were calculated, using the partial pressures of the vapor, p_v, and the dry air, p_a. The partial pressure of the dry air could be further broken down as the difference between the pressure of the ambient air and the vapor.

$$\omega = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p_{amb} - p_v} \qquad [3]$$

Furthermore, the values for the inlet and exit humidity ratios could be determined using Table B1.1 for saturated water; since all the values were measured, interpolation was used to find each unique partial pressure for the vapor. In this example, data from Test 1 was used to calculate the humidity ratios. The ambient pressure of the air in Gainesville, FL was measured to be 101.325 kPa.

$$\omega_1 = 0.622\left(\frac{1.485\,\cancel{kPa}}{101.325\,\cancel{kPa} - 1.485\,\cancel{kPa}}\right) = 0.00925$$

$$\omega_2 = 0.622\left(\frac{1.806\,\cancel{kPa}}{101.325\,\cancel{kPa} - 1.806\,\cancel{kPa}}\right) = 0.01129$$

Next, the relative humidity was determined for each test condition. Ultimately, the psychometric chart was utilized to find these values, but the relative humidity could be calculated using the partial pressures of the vapor and the gas.

$$\varphi = \frac{p_v}{p_g} \qquad [2]$$

The enthalpy of the water entering the cooling tower is found by interpolating between values provided by Table B.1.1 in the *Fundamentals of Thermodynamics*, *10th* edition textbook For Test 1, $T_5 = 23$ ℃, so h_3 is between 83.94 kJ/kg and 104.87 kJ/kg.

$$h_3 = 96.498\frac{kJ}{kg}$$

To calculate the density of the air-vapor mixture, first the density of the dry air leaving the cooling tower had to be found. The equation was derived from the Ideal Gas Law and further broken down to incorporate the pressure of the vapor at the cooling tower's exit, $p_{v,2}$, and the exit humidity ratio, ω_2.

$$\rho_a = \frac{p_a}{R_a T_a} = \frac{0.622\left({}^{p_{v,2}}/_{\omega_2}\right)}{R_a(T_a + 273.15)} \qquad [3]$$

This example utilizes values from Test 1, including T_4, the temperature of the wet bulb at the outlet.

$$\rho_a = \frac{0.622\left({}^{1806\,\cancel{Pa}}/_{0.01129}\right)\frac{\cancel{N}/m^2}{P\cancel{a}}\frac{kg\cdot\cancel{m/s^2}}{\cancel{N}}}{287\frac{\cancel{J}}{\cancel{kg\cdot K}}(15.8\text{ ℃} + 273.15\,K)\frac{\cancel{kg}\cdot m^{\cancel{2}}/\cancel{s^2}}{\cancel{J}}} = 1.20\frac{kg}{m^3}$$

Subsequently, the density of the air-vapor mixture exiting the tower was determined. This equation combines the density of the dry air leaving the cooling tower, ρ_a, with the humidity ratio at the exit, ω_2.

$$\rho_{mix} = (1 + \omega_2)\rho_a \qquad [4]$$

This example follows the previous calculation, utilizing data from Test 1.

$$\rho_{mix} = (1 + 0.01129)\left(1.20\frac{kg}{m^3}\right) = 1.2136\frac{kg}{m^3}$$

Next, the mass flowrate of the air leaving the cooling tower was found. This equation was reliant on the calculated density of the air-vapor mixture exiting the tower, ρ_{mix}, and the collected data for the pressure drop of the air, ΔP.

$$\dot{m}_a = 0.0137\sqrt{\rho_{mix}\Delta P} \qquad [4]$$

This example uses data from Test 1 and the previously calculated value of ρ_{mix}.

$$\dot{m}_a = 0.0137\sqrt{\frac{kg \cdot \cancel{m^3}}{s^2 \cdot \cancel{mmH_2O}}} \times \sqrt{1.2136\frac{kg}{\cancel{m^3}} \times 10\,\cancel{mmH_2O}} = 0.0477\frac{kg}{s}$$

After computing the necessary values, mass and energy balances of the cooling tower system could be configured. The following equations represent the mass balance for the control volume, ending with a value for the mass flowrate out of the tower from the water, $\dot{m}_4$. This relates enthalpy from the mixture into and out of the system with enthalpy from the water into and out of the system.

$$\dot{m}_a h_1 + \dot{m}_3 h_3 = \dot{m}_a h_2 + \dot{m}_4 h_4 \qquad [1]$$

$$\dot{m}_4 = \dot{m}_3 + \dot{m}_a(\omega_1 - \omega_2)$$

This value was calculated using data from Test 1.

$$\dot{m}_4 = 20\frac{\cancel{g}}{s}\frac{1\,kg}{1000\,\cancel{g}} + 0.0477\frac{kg}{s} \times (0.00925 - 0.01129) = 0.0199\frac{kg}{s}$$

Finally, the predicted enthalpy of the water leaving the cooling tower was calculated from rearranging the energy balance equation.

$$h_{4,predicted} = \frac{\dot{m}_a(h_1 - h_2) + \dot{m}_3 h_3}{\dot{m}_4} \qquad [1]$$

The value was determined using data from Test 1.

$$h_{4,predicted} = \frac{0.0477\frac{\cancel{kg}}{\cancel{s}} \times \left(56\frac{kJ}{\cancel{kg}} - 64\frac{kJ}{\cancel{kg}}\right) + 20\frac{\cancel{g}}{\cancel{s}}\frac{1\,\cancel{kg}}{1000\,\cancel{g}} \times 96.498\frac{kJ}{\cancel{kg}}}{0.0199\frac{kg}{\cancel{s}}} = 77.79\frac{kJ}{kg}$$

Using the predicted enthalpy of the water leaving the cooling tower, the predicted exit temperature of the water is found by interpolating between values provided by Table B.1.1 in the *Fundamentals of Thermodynamics, 10th* edition textbook. As $h_{4,predicted} = 77.79\ kJ/kg$, $T_{6,predicted}$ is between 15 ℃ and 20 ℃.

$$T_{6,predicted} = 18.53\ ℃$$

As the heat transfer process undergoing in the cooling tower is not perfectly effective, to predict the heat dissipation rate, the following equation is used,

$$Q_{predicted} = \dot{m}_3 h_3 - \dot{m}_4 h_{4,predicted} \qquad [1]$$

The value was determined using data from Test 1.

$$Q_{predicted} = 20 \frac{\cancel{g}}{s} \frac{1\ \cancel{kg}}{1000\ \cancel{g}} \times 96.498 \frac{kJ}{\cancel{kg}} - 0.0199 \frac{\cancel{kg}}{s} \times 77.79 \frac{kJ}{\cancel{kg}} = 0.382\ kW$$

The actual heat dissipation rate can be found by replacing the predicted enthalpy of the water leaving the cooling tower with the actual value of the enthalpy of the water leaving. The value for h_4 is determined by interpolating between values provided by Table B.1.1 in the *Fundamentals of Thermodynamics, 10th* edition textbook. h_4 is between $62.98\ kJ/kg$ and $83.94\ kJ/kg$.

$$h_4 = 69.69\ kJ/kg$$

$$Q = \dot{m}_3 h_3 - \dot{m}_4 h_4 \qquad [1]$$

The value was determined using data from Test 1.

$$Q = 20 \frac{\cancel{g}}{s} \frac{1\ \cancel{kg}}{1000\ \cancel{g}} \times 96.498 \frac{kJ}{\cancel{kg}} - 0.0199 \frac{\cancel{kg}}{s} \times 69.69 \frac{kJ}{\cancel{kg}} = 0.543\ kW$$

Table 3: Original data from six experiments run in lab. As calculations required utilize temperatures in Kelvin, all temperature data points were converted to Kelvin to aid in cross-referencing data with calculations. During the experiment, Heating Power, Water Mass Flow Rate, and ΔP_{air} were all test variables controlled by equipment. The $T_1 - T_6$ temperature data points were measured for each test iteration after temperatures were observed to reach equilibrium. An observation from the following data is that as water mass flow increases, the difference between water inlet and water outlet decreases.

Test	**Heating Power [kW]**	**Water Mass Flow Rate [g/s]**	**ΔP_{air} [mmH_2O]**	**Air Dry In T_1 [K]**	**Air Wet In T_2 [K]**	**Air Dry Out T_3 [K]**	**Air Wet Out T_4 [K]**	**Water Inlet T_5 [K]**	**Water Outlet T_6 [K]**
1	0.5	20	10	292.4	285.9	290.6	289.0	296.2	289.8
2	0.5	30	10	292.4	285.8	290.4	288.9	293.8	289.9
3	0.5	40	10	292.4	285.9	290.4	289.0	292.9	290.1
4	1.5	20	10	292.5	285.9	293.2	291.8	305.0	292.3
5	1.5	30	10	292.5	285.9	293.4	291.9	302.1	292.8
6	1.5	40	10	292.5	285.9	293.2	291.8	299.9	293.1

References

[1] Abbitt, John. “Cooling Tower Pre-Lab Video.” University of Florida, Gainesville, FL.

[2] Schulze, Kurt. “Cooling Tower 2 Lecture Notes.” University of Florida, Gainesville, FL. 6/20/2023.

[3] Schulze, Kurt. “Cooling Tower 4 Lecture Notes.” University of Florida, Gainesville, FL. 7/11/2023.

[4] Abbitt, John. “Cooling Tower Lab Procedure.” University of Florida, Gainesville, FL.

Lab Report Participation Log

Name	**Date**	**Hours Worked**	**Description of Tasks Performed**
Alli Porras	7/11	1	Set up report document with sections and tables
Everyone	7/16	1	Distributed tasks
Conor Bowman	7/19	2	Worked on original data sheet and formatting
Everyone	7/20	1	Checked in a few times and talked through some calculations together
Alli Porras	7/20	1	Worked on calculations for first law analysis
David Reyes	7/20	1	Started working on providing sample calculations
Alli Porras	7/21	2	Finished calculations, added values into Table 2, and worked on sample calculations
Conor Bowman	7/21	3	Finished cover letter, some overall formatting
Alex Carr	7/21	2	Calculated humidity ratio and relative humidity values and formatted tables
David Reyes	7/21	2	Calculated the density of air and the mixture. Calculated all mass flow rates. Calculated heat dissipation rate and did some interpolation calculations.
	Total Hours:	16	