COOLING TOWER PERFORMANCE

OBJECTIVES
This experiment analyzes the operation and performance of a laboratory-size water cooling tower. Performance will be assessed for varying water inlet temperatures. The main objectives of this exercise are:

1. To observe the operation of a water cooling tower.
2. To assess the performance of the cooling tower in terms of its ability to cool hot water.
3. To perform a mass balance and energy balance on the cooling tower.

INTRODUCTION
The cooling tower is a free-standing, open, recycling evaporative cooling device. Its purpose is to cool liquid water, and it does so by two mechanisms. The primary cooling mechanism is through evaporation, in which water undergoes a phase change from a liquid to a vapor. The heat of vaporization is provided by the hot water, which is cooled as a result of this heat loss. The secondary mechanism is a combination of convection and radiation heat transfer from the liquid water to air (and the surroundings in the case of radiation), which is a result of the temperature difference between the two.

The cooling tower operates in a counter-flow mode with the air traveling upward over the downward moving water. In an actual application, the water cooled by the tower is re-circulated to a condenser where it absorbs heat, thereby increasing its temperature before being returned to the cooling tower to complete the cycle. In the present experiment, the condenser (used in industrial applications) is replaced by a set of two individually-controlled water heaters. These heaters along with the inlet water flow and air flow rates can be adjusted so that a fixed temperature is established for the water entering the cooling tower. Also, according to the equipment manual, the amount of heat added to the water due to the water pump is 100 W.

The cooling tower is equipped with thermocouples, a flow meter, and a manometer so that all quantities contributing to both mass and energy balances can be measured. Control variables include air flow rate, water flow rate, and heating rate. These variables will all contribute to the inlet water temperature. Cooling tower performance will be evaluated primarily as a function of inlet water temperature. Schematic diagrams of the cooling tower are shown in (figs. 1 – 3). The water flow loop is shown in (fig. 1). The air distribution system, including a fan and an orifice, and temperature measurement locations, are shown in (fig. 2). The primary controls for system operation are shown in (fig. 4).

PROCEDURE
Cooling tower operation requires the control of three different sub-systems: (1) the water supply, (2) the air flow, and (3) water heaters. The water loop will be started at a constant flow rate of approximately 40 g/s by either the lab technician or the TA and will be varied later in the lab. The pump is turned on by the main switch (fig. 4). A volumetric flow meter (shown in figs. 1 and 4) provides a measurement of the water flow rate to the cooling tower. The flow is controlled by the valve on top of the meter.

The fan is also started with the main switch (fig. 4). The air flow entering the fan can be adjusted using the intake damper (fig. 2). **In this experiment the damper should be set so the orifice at the outlet of the**

tower has a pressure difference of 10 mmH$_2$O. This pressure difference can be read with the manometer (fig. 4) on the control panel by attaching the long hose to the top pressure tab on the tower (fig. 3).

Water collected in a basin beneath the cooling tower is pumped back to the main water tank. In the main tank there is a 0.5 kW heater and a 1.0 kW heater giving options of 0.5 kW, 1.0 kW, and 1.5 kW to heat the water. These heaters can be controlled by switches on the control panel (fig. 4). The heaters can be used to adjust the water inlet temperature. **In this experiment the heaters will be set to 1.5 kW the entire time.**

The water inlet temperature (T_5 on the temperature indicator on the control panel) should never exceed 50°C (122°F). Thermocouples for water inlet and outlet along with air inlet and outlet wet and dry bulb temperatures are connected to a multi-point (push button) digital temperature indicator located on the control panel. The wet bulb reservoirs will have already been filled with water by either the TA or the lab technician. Channels and corresponding temperatures for the indicator are:

Channel	Symbol	Position	Temperatures
1	T_1	Air inlet (A)	Dry-bulb temperature
2	T_2		Wet-bulb temperature
3	T_3	Air outlet (B)	Dry-bulb temperature
4	T_4		Wet-bulb temperature
5	T_5	Water inlet	Water temperature
6	T_6	Water outlet	Water temperature

Water and dry and wet bulb temperatures for air will be measured at three locations inside the cooling tower (F, G, H in fig. 3) using a temperature indicator mounted on the side of the column. Channels and corresponding temperatures for the side mounted temperature indicator are:

Channel	Symbol	Position	Temperatures
1	t_1	H (H_t = 71.8 cm)	Air, wet-bulb
2	t_2		Air, dry-bulb
3	t_3		Water
4	t_4	G (H_t = 48.3 cm)	Air, wet-bulb
5	t_5		Air, dry-bulb
6	t_6		Water
7	t_7	F (H_t = 24.8 cm)	Air, wet-bulb
8	t_8		Air, dry-bulb
9	t_9		Water

Note that in the write-up lower case <u>t</u> refers to temperature readings on the <u>side mounted indicator</u> and upper case <u>T</u> refers to temperature readings on the <u>indicator on the control panel</u>.

The procedure for establishing the desired test conditions and conducting the data acquisition follows. State points for the air outlet and inlet, liquid water outlet and inlet, and air/water vapor mixture are identified in Figs. 1-3.

1. Make sure make up tank is filled to the mark. Check make up tank frequently.
2. Set the air damper so the orifice differential pressure is approximately 10 mmH$_2$O.
3. Make sure both heaters are on so there is 1.5 kW of heat.

4. Adjust the flow valve so the water inlet flow rate is approximately ___ g/s. When changing the flow rates it may take 10 to 15 minutes to reach steady state. Check the flow rate indicator and adjust it if necessary to maintain a steady flow rate.
5. Record the following data.
   a) Barometric pressure P_{amb} (mm mercury) using the barometer next to the door of the lab.
   b) Water temperature at the cooling tower inlet T_5 and outlet T_6 using the indicator on the control panel.
   c) Water flow rate into the cooling tower using the flow meter.
   e) Dry bulb temperatures (t_2, t_5, t_8) and wet bulb temperatures (t_1, t_4, t_7) of the air/water vapor mixture along with water temperatures (t_3, t_6, t_9) within the cooling tower at the three different vertical positions (F, G, H; fig. 3) using the temperature indicator mounted on the side of the column.
   f) Dry bulb temperatures (T_1 and T_3) and wet bulb temperatures (T_2 and T_4) of the air/water vapor mixture at the inlet (A) and exit (B) of the cooling tower using the digital temperature indicator on the control panel (fig. 2).
   g) Difference from ambient pressure and the bottom pressure tap using the manometer at the inlet of the tower: ΔP_A
   h) Orifice differential pressure using the manometer at the outlet of the tower, ΔP_B (should be about 10 mmH_2O as stated above)
6. Repeat steps 5(b)-5(g). for water inlet flow rates of ____ g/s and ____ g/s. Wait for temperatures to stabilize before recording. This can take 10 to 15 minutes. Do not adjust the air damper or the heater settings.
7. Turn off the heaters using the switches on the control panel.
8. Turn of the main switch.
9. Further system shut-down procedures will be conducted by the TA or the lab technician.

DATA REDUCTION

The following data reduction process should be completed for each data set corresponding to the three water inlet flow rates. Refer to figs. 1-3 for temperature locations. Assumptions and idealizations for this analysis include: the system is operating at steady state, changes in potential and kinetic energy are negligible, the dry air and water vapor are ideal gases, total pressure for the air/water vapor mixture within the cooling tower is equivalent to the measured atmospheric pressure, and properties of compressed liquid water can be approximated using properties at the saturated liquid state at the same temperature.

1. Determine **the mass flow rate of dry air** using the following procedure.
   a. Use **the attached psychrometric chart** (for ambient pressure P_{amb} = 84.6 kPa) to determine the specific volume (v), relative humidity (ϕ), and absolute humidity (ω) at the tower inlet (A) and outlet (B).
   b. Determine the saturation pressure of the water vapor P_{gA} at temperature T_1 and P_{gB} at temperature T_3 from the following general correlation for water [1].

$$
\begin{aligned}
P_g = 22.064\times10^3 \exp\{647.096/T*(-7.85951783\xi + 1.84408259\xi^{1.5} - 11.7866497\xi^3 \\
+ 22.6807411\xi^{3.5} - 15.9618719\xi^4 + 1.80122502\xi^{7.5})\}
\end{aligned}
\tag{1}
$$

with T in (K) and P_g in (kPa) and $\xi = 1 - T/647.096$. ξ is unitless.

c. Determine the absolute humidity (ω) at the tower inlet (A) and outlet (B) using the appropriate relationship from [2].

$$\omega_{\mathrm{A}} = \frac{0.622\phi_{\mathrm{A}} P_{g\mathrm{A}}}{P_{\mathrm{A}} - \phi_{\mathrm{A}} P_{g\mathrm{A}}} \quad \text{and} \quad \omega_{\mathrm{B}} = \frac{0.622\phi_{\mathrm{B}} P_{g\mathrm{B}}}{P_{\mathrm{B}} - \phi_{\mathrm{B}} P_{g\mathrm{B}}} \tag{2}$$

Compare these values with the values found using the attached psychrometric chart.

d. Use Amagat's law of additive volume to compute the air/water vapor mixture specific volume v_1 (m^3/kg dry air) from the following equation, which was derived by dividing the total volume by $\dot{m}_a$ [3]:

$$v_{\mathrm{A}} = v_{a\mathrm{A}} + \omega_{\mathrm{A}} v_{v\mathrm{A}} \quad \text{and} \quad v_{\mathrm{B}} = v_{a\mathrm{B}} + \omega_{\mathrm{B}} v_{v\mathrm{B}} \tag{3}$$

The specific volume (m^3/kg) for dry air v_a and for the water vapor v_v at the tower inlet (A) and outlet (B) from the ideal gas equation of state and the appropriate values of pressure and gas constant [1]:

$$v_{a\mathrm{A}} = \frac{R_a T_1}{P_{\mathrm{A}}} \left(\text{or } v_{a\mathrm{B}} = \frac{R_a T_3}{P_{\mathrm{B}}} \right) \quad \text{and} \quad v_{v\mathrm{A}} = \frac{R_v T_1}{P_{\mathrm{A}}} \left(\text{or } v_{v\mathrm{B}} = \frac{R_v T_3}{P_{\mathrm{B}}} \right) \tag{4}$$

where the gas constant for air R_a = 0.287 kPa-m^3/kg-K and the gas constant for water vapor R_v = 0.4615 kPa-m^3/kg-K. It should be noted that P_{A} and P_{B} are the pressure of the air/water mixture at the inlet and outlet of the tower, respectively, and can be expressed as $P_{\mathrm{A}} = P_{amb} + \Delta P_{\mathrm{A}}$ and $P_{\mathrm{B}} = P_{amb} + \Delta P_{\mathrm{B}}$, where ΔP_{A} and ΔP_{B} are measured pressure values with the manometer.

Compare these values with the values found using the attached psychrometric chart.

f. Use the orifice calibration below to calculate the mass flow rate of dry air.

$$\dot{m}_a = 0.0137\sqrt{\frac{\Delta P_B}{(1+\omega_B)v_B}} \tag{5}$$

where ΔP_{B} is the orifice pressure differential **in mmH$_2$O**, ω_{B} is the absolute humidity at the tower exit, and v_{B} is the specific volume of the air/water vapor mixture leaving the tower.

2. Use the water property tables in [2] to determine **the specific enthalpy of the liquid water** at the tower inlet (5) and outlet (6).

3. Use the attached psychrometric chart to determine **the absolute humidity** ω for the 3 state points within the tower (F, G, H) associated with the air/water vapor mixture.

4. Determine **the mass flow rate of water vapor** at states A and B, $\dot{m}_{vA}$ and $\dot{m}_{vB}$ (kg/s), using the following equation (shown for state A):

$$\dot{m}_{vA} = \omega_A \dot{m}_a \tag{7}$$

5. Determine **the enthalpy of the air/water vapor mixture** at states A and B, h_A and h_B (kJ/kg), from the following equation (shown for state A):

$$h_A = c_p T_1 + \omega_A h_{gA} \tag{8}$$

where c_p = 1.005 kJ/kg-K for dry air, T_1 (°C) and h_{gA} (kJ/kg) can be approximated by

$h_{gA} = 2500.9 + 1.82\ T_1$ (T_1 in °C)

Also, determine these values of enthalpy using the attached psychrometric chart and compare them to your results using eq. (8) above.

6. Determine **the mass flow rate of liquid water** exiting the cooling tower at state 6, $\dot{m}_6$ (kg/s), by applying the mass conservation of water vapor and of liquid water in the cooling tower. Use the calculated values above.

7. Determine **the required mass flow rate of makeup water**, $\dot{m}_{makeup}$ (kg/s), to the main tank by applying conservation of mass (rate form) on the liquid water in the tank. Use the calculated values above for this.

8. Determine **the total heat gain of the air**, $\dot{Q}_{air}$ (kW), as it passes through the tower and compare this result to the total input power of the setup. Note that the pump input is approximately 100 W.

9. The cooling tower is not insulated and is therefore not adiabatic. Determine **the rate of heat gain/loss to/from the cooling tower**, $\dot{Q}_{amb}$ (kW), by applying the First Law of Thermodynamics (rate form) to the cooling tower.

10. Determine the **range** ($T_{w,in}$ - $T_{w,out}$) and the **approach** ($T_{w,out}$- $T_{wb,in}$), in °C, for the cooling tower based on your measurements at each flow rate.

PRESENTATION OF RESULTS

1. On a single figure, plot absolute humidity as a function of cooling tower height (4 positions; A=0 cm, F=24.8cm, G=48.3cm, H=71.8cm) for all three water inlet flow rates. Include a legend that indicates the water inlet flow rates in kg/s. Use markers to plot the individual data points in each data set. Use a different marker for each flow rate.
2. On a single figure, plot dry bulb temperature as a function of cooling tower height (4 positions; A, F, G, H) for all three water inlet flow rates. Include a legend that indicates the water inlet flow rates in kg/s. Use markers to plot the individual data points in each data set. Use a different marker for each flow rate.
3. Plot the ratio of the water outlet mass flow rate, $\dot{m}_6$, to water inlet mass flow rate, $\dot{m}_5$, as a function of inlet water temperature, T_5.
4. Plot $\dot{Q}_{air}$ and $\dot{Q}_{amb}$ as a function of inlet water temperature, T_5.

ITEMS FOR DISCUSSION

1. How do the trends in the dry bulb temperature and absolute humidity as a function of height compare with each other? Describe briefly what happens (physically) to the air passing through the tower from point A to point B.

2. Discuss the effect that the inlet water temperature T_5 has on $\dot{m}_6$ and $\dot{m}_{makeup}$. Provide a physical explanation for the exhibited trend. Is there a connection to the change in absolute humidity ($\omega_B - \omega_A$) for the air/water vapor mixture?
3. Discuss how $\dot{Q}_{amb}$ is affected by changes in T_5. Provide a physical explanation for the effect.

REFERENCES

1. The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use, W. Wagner and A. Pruss, *J. Phys. Chem. Ref. Data*, 31, 387-535, 2002.
2. *Thermodynamics, An Engineering Approach*, 7th Ed., Y.A. Cengel and M.A. Boles, McGraw-Hill, 2011.
3. *Thermodynamics*, E.E. Anderson, PWS Publishing Co., Boston, MA, 1994.
4. Water Quality, McCutcheon, S.C., Martin, J.L., Barnwell, T.O., Jr., in *Handbook of Hydrology*, Maidment, D.R. (ed.),McGraw-Hill, New York, NY, p. 11.3, 1993.

Footnotes:

1. In Amagat's model, component T = mixture T, component P = mixture P, mixture volume = sum of component volumes. This model is used because in Lab 3 the mixture P is easy to measure.
2. The mixture specific volume, v in Eq. (5), is defined as: mixture volume/mass of dry air.

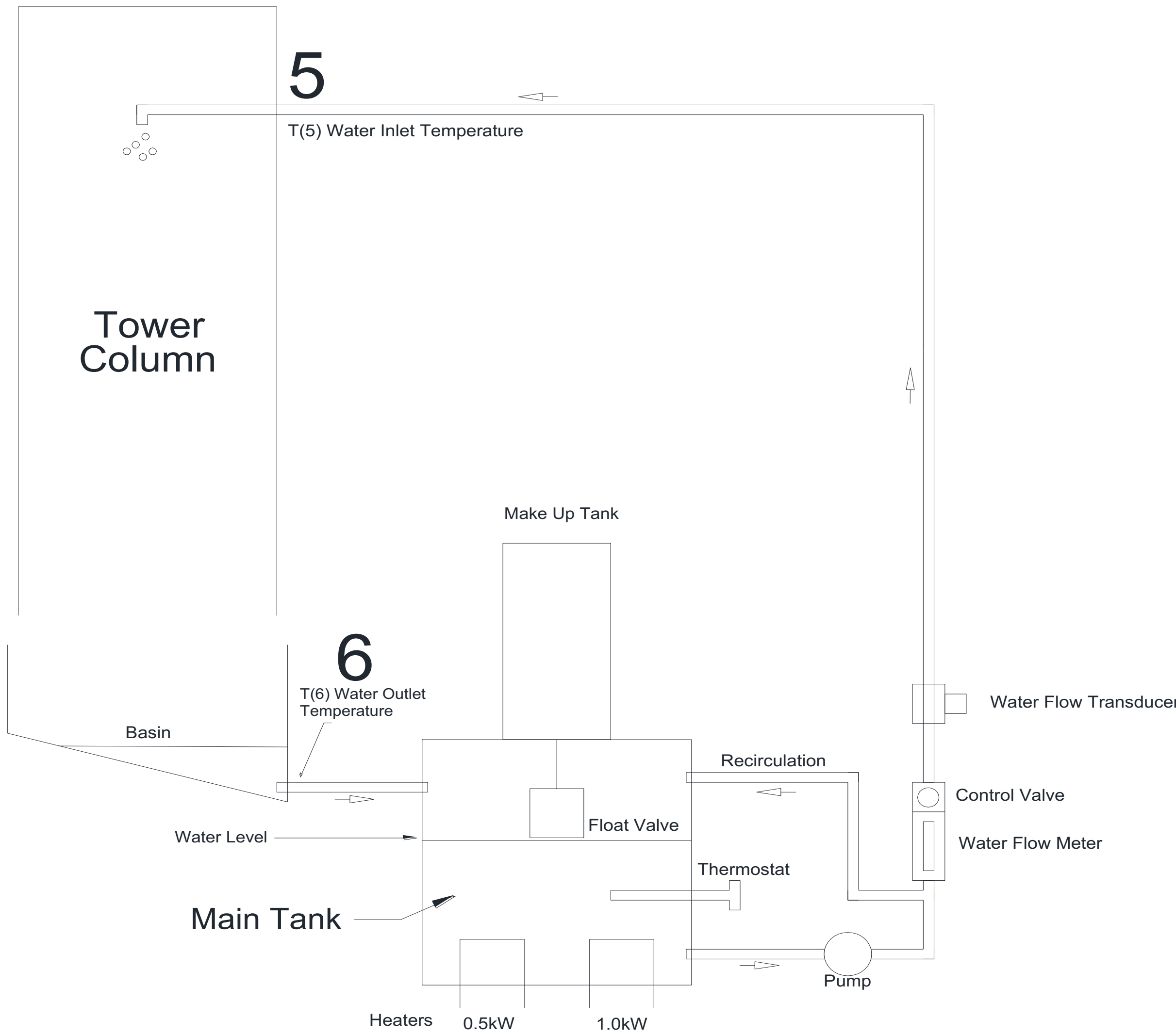


Figure 1. Cooling Tower Water Loop.

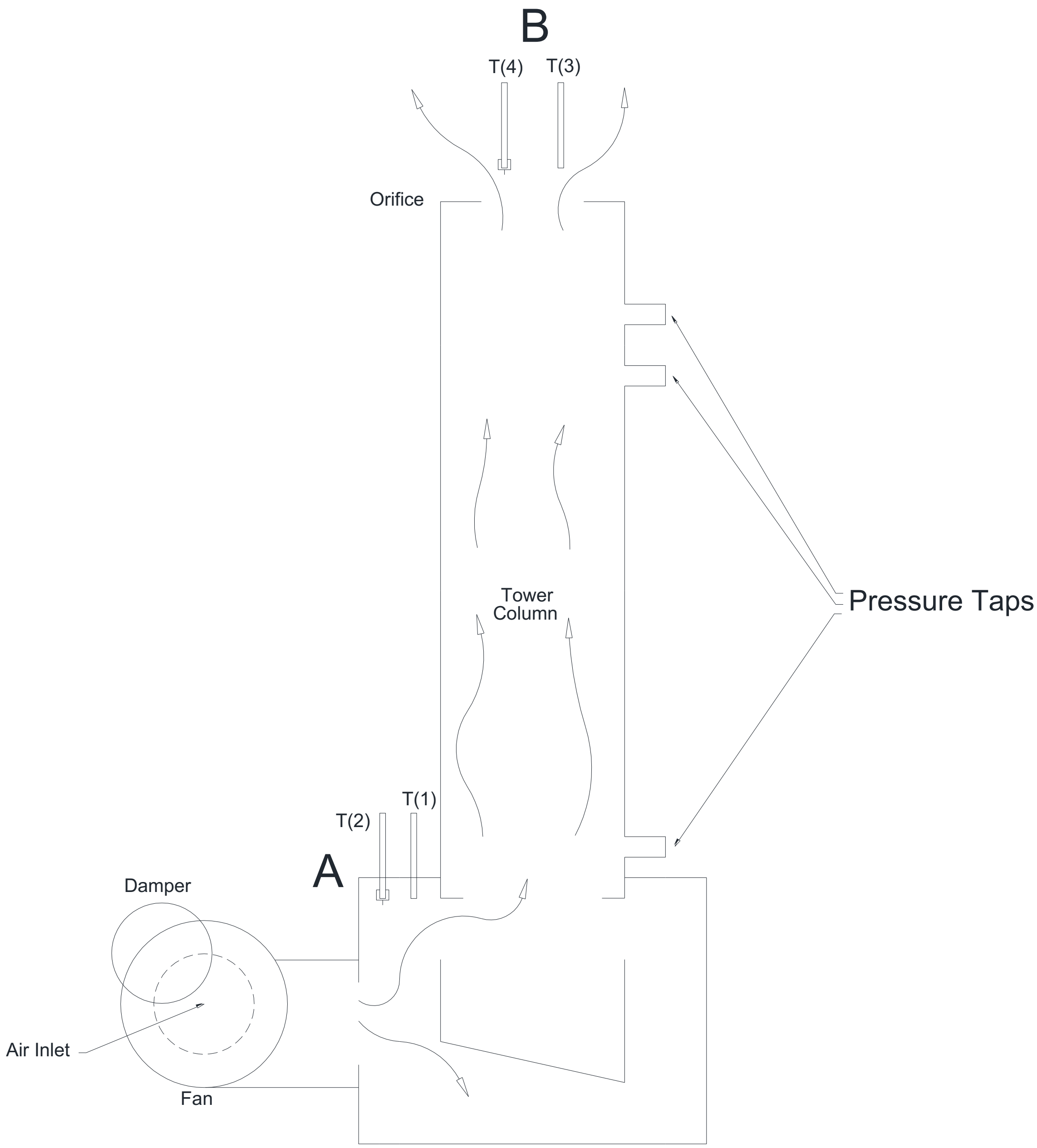


Figure 2. Cooling Tower Air Path

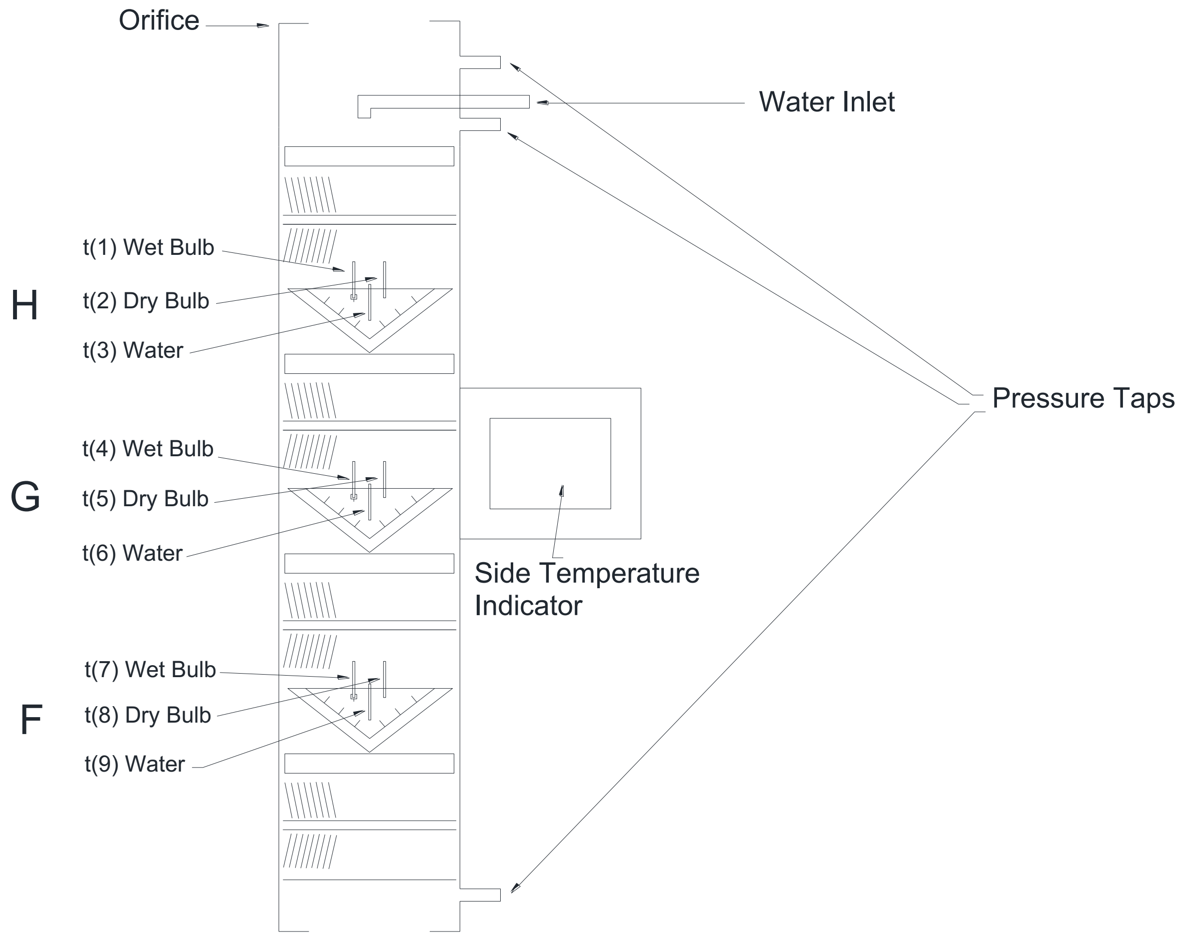


Figure 3. Tower Column

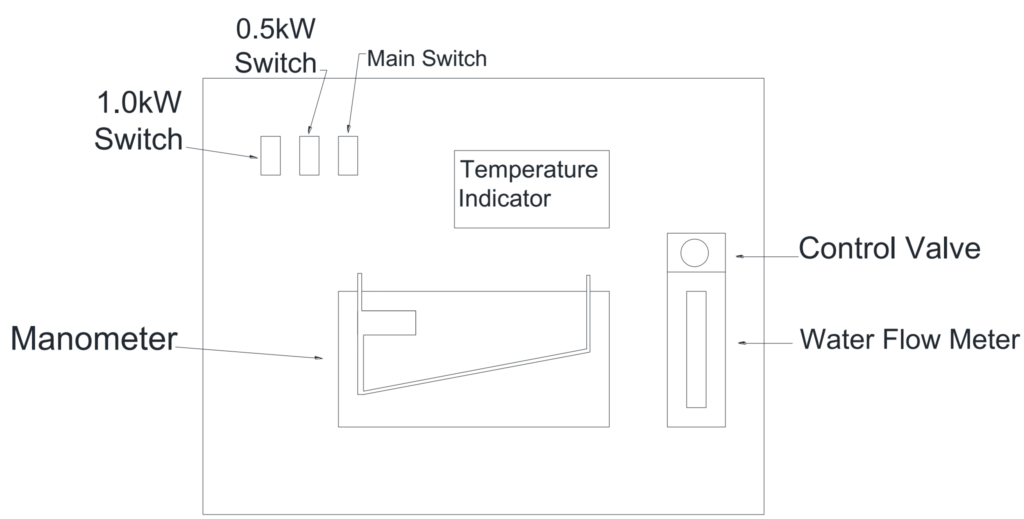


Figure 4. Control Panel

Carrier

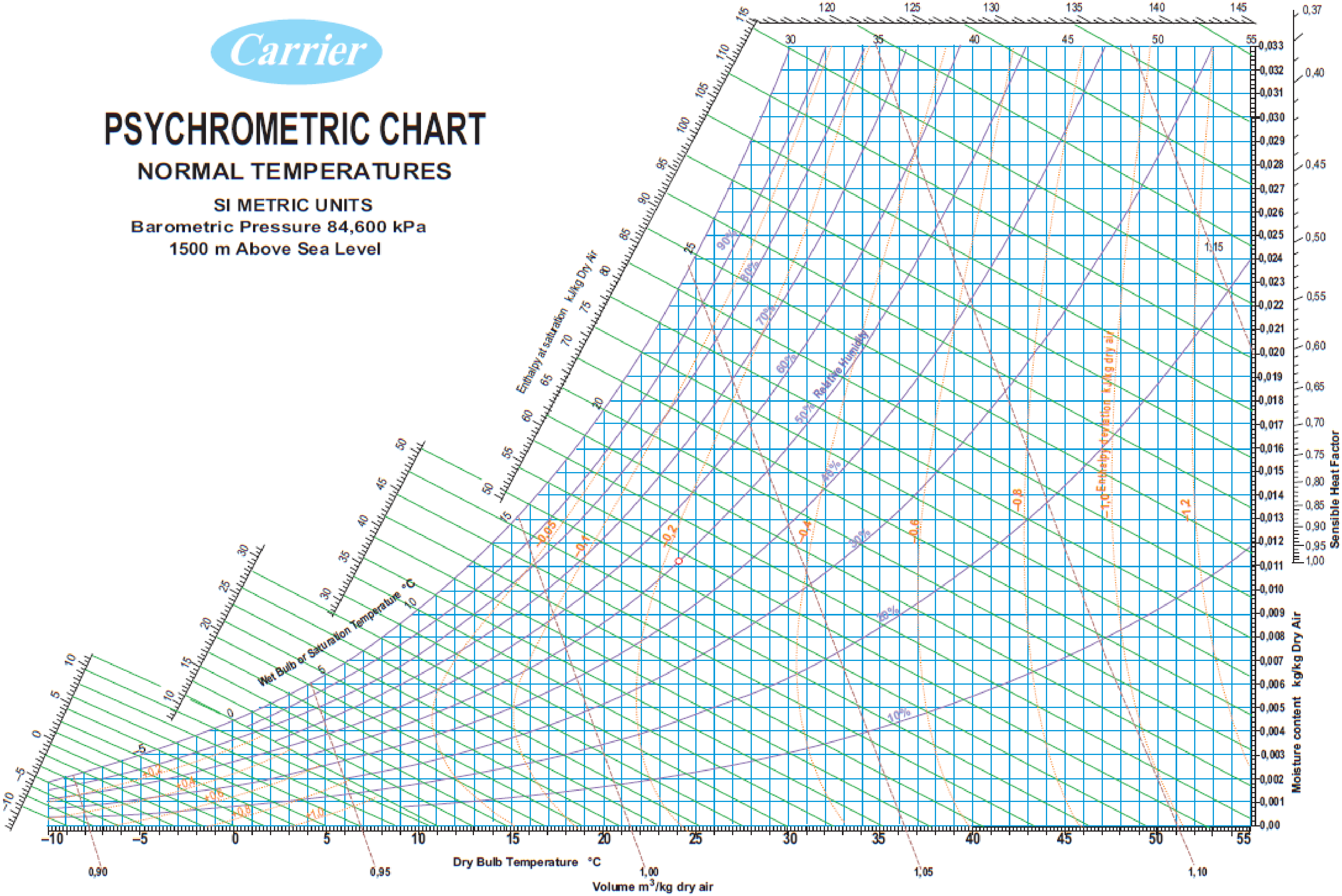
PSYCHROMETRIC CHART

NORMAL TEMPERATURES

SI METRIC UNITS

Barometric Pressure 84,600 kPa

1500 m Above Sea Level



Below 0°C, Properties and Enthalpy Deviation Lines Are For Ice