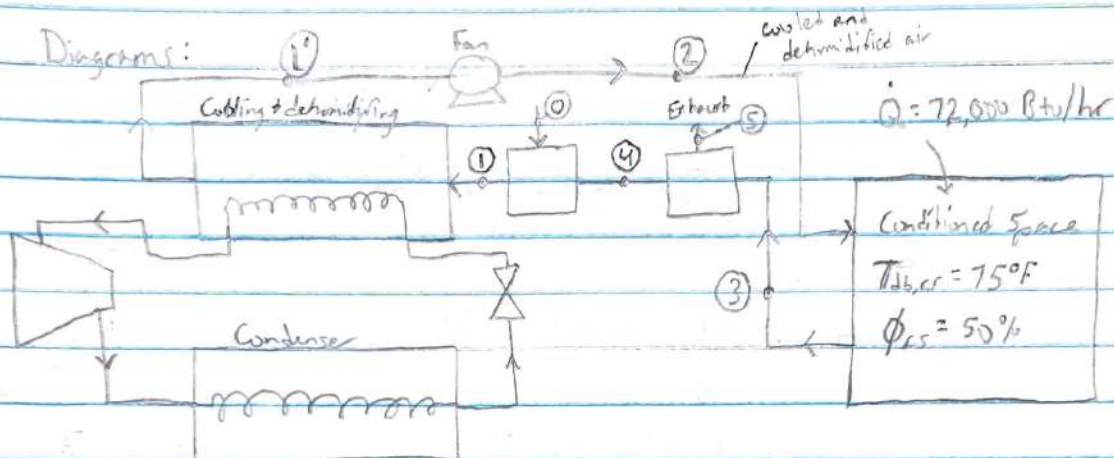


11) Purpose: Determine the quantity of air supplied to the space, state of air at each state, processes shown on psychrometric chart, the capacity of the cooling and dehumidifying unit, and the amount of liquid water drained in cooling and dehumidifying unit.



Sources: Cengel, Boles, and Kanoglu. Thermodynamics, An Engineering Approach. 9th Edition. McGraw Hill. 2020.

Design Considerations:

- Steady operating condition
- Dry air and water vapor are ideal gases
- Kinetic and potential energy changes are negligible
- Cooling and dehumidifying process follows ideal behaviour
- Assume fan is ideal
- Assume 1 atm

Date and Variable:

$$T_{\text{dew}} = 75^\circ\text{F} = 24^\circ\text{C}$$

$$\phi = 50\%$$

$$\dot{Q} = 72,000 \text{ Btu/hr} = 21.1 \text{ kJ/s}$$

$$Q = 500 \text{ cfm} = 0.2359 \text{ m}^3/\text{s}$$

$$T_{\text{dry, outside}} = 90^\circ\text{F} = 32^\circ\text{C}$$

$$\phi_{\text{dry, calc'd}} = 60\%$$

Materials: Air

Procedure: I will use 1st law for the conditioned space and determine the properties for each state.

Inside conditioned space, using psychrometric chart:

$$T_{db,i} = 24^{\circ}\text{C}$$

$$\phi_{i,s} = 50\%$$

$$h_{i,s} = 47.9 \text{ kJ/kg dry air}$$

$$w_{i,s} = 0.0093 \text{ kg water/kg dry air}$$

$$v_{i,s} = 0.854 \text{ m}^3/\text{kg dry air}$$

$$T_{wb,i} = 17^{\circ}\text{C}$$

$$P_{sat @ 17^{\circ}\text{C}} = 1.96 \text{ kPa (Table A-4, interpolated using calculator)}$$

Outside space using psychrometric chart:

$$T_{db,out} = 32^{\circ}\text{C}$$

$$\phi_{out} = 60\%$$

$$h_{out} = 78 \text{ kJ/kg dry air}$$

$$v_{out} = 0.899 \text{ m}^3/\text{kg dry air}$$

$$T_{wb,out} = 25.5^{\circ}\text{C}$$

$$P_{sat @ 25.5} = 3.28 \text{ kPa (Table A-4, interpolated using calculator)}$$

$$w_{out} = 0.0183 \text{ kg water/kg dry air}$$

$$Q_{sensible} = 21.1 \text{ kJ/s}$$

$$\dot{V} = 500 \text{ cfm} = 0.2359 \text{ m}^3/\text{s}$$

$$\rho_{air} = \frac{P}{RT} = \frac{101.33 \text{ kPa}}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(305 \text{ K})} = 1.158 \text{ kg/m}^3$$

$$\dot{m}_{air} = \dot{V} \rho_{air} = (0.2359 \frac{\text{m}^3}{\text{s}})(1.158 \frac{\text{kg}}{\text{m}^3}) = 0.273 \text{ kg/s}$$

$$\dot{Q}_{\text{latent}} = \dot{m}_{\text{air}} C_p (T_{\text{out}} - T_{\text{in}})$$

$$= (0.273 \frac{\text{kg}}{\text{s}})(1.005 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}})(32^\circ\text{C} - 24^\circ\text{C})$$

$$\dot{Q}_{\text{latent}} = 2.19 \text{ kJ/s}$$

$$\dot{W}_{\text{as}} = \dot{W}_{\text{out}}$$

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{ensible}} - \dot{Q}_{\text{latent}}$$

$$= 21.1 \frac{\text{kJ}}{\text{s}} - 2.19 \text{ kJ/s}$$

$$\dot{Q}_{\text{total}} = 18.91 \text{ kJ/s}$$

See next sheet for states

B.)

(Outside)

②

$$\dot{V} = 0.2359 \text{ m}^3/\text{s}$$

$$T_{db,o} = 32^\circ\text{C}$$

$$\phi_o = 60\%$$

$$\omega_o = 0.0183 \frac{\text{kg water}}{\text{kg dry air}}$$

$$\dot{m}_o = 0.273 \text{ kg/s}$$

$$h_o = 78.5 \text{ kJ/kg dry air}$$

①

$$\phi = 100\%$$

$$\dot{m}_1 = 2.21 \text{ kg/s}$$

$$h_1 = 51.3 \text{ kJ/kg dry air}$$

$$\omega_1 = 0.0101 \frac{\text{kg water}}{\text{kg dry air}}$$

$$T_{db,1} = 27.3^\circ\text{C}$$

①

②

$$T_{2,i} = 14.5^\circ\text{C}$$

$$\phi_2 = 50\%$$

$$\omega_2 = 0.0093 \frac{\text{kg water}}{\text{kg dry air}}$$

$$h_2 = 47.5 \text{ kJ/kg dry air}$$

$$\dot{m}_2 = 0.546 \text{ kg/s}$$

(Return Air)

③

$$T_{3,i} = 24^\circ\text{C}$$

$$\omega_3 = \omega_2 = 0.0093 \frac{\text{kg water}}{\text{kg dry air}}$$

$$\dot{Q}_m = 21.1 \text{ kW}$$

$$\phi_3 = 50\%$$

$$h_3 = 47.5 \text{ kJ/kg dry air}$$

$$\dot{m}_3 = 0.546 \text{ kg/s}$$

$$h_3 = 47.5 \text{ kJ/kg dry air}$$

④

$$\dot{V}_4 = \dot{V}_2 = 0.2359 \text{ m}^3/\text{s}$$

$$T_{4,db} = T_{3,db} = 24^\circ\text{C}$$

$$\phi_4 = \phi_3 = 50\%$$

$$h_4 = h_3 = 47.5 \text{ kJ/kg}$$

$$\dot{m}_4 = 1.94 \text{ kg/s}$$

$$\omega_4 = 0.009 \frac{\text{kg water}}{\text{kg air}}$$

(Exhaust)

⑤

$$\dot{V}_5 = 0.2359 \text{ m}^3/\text{s}$$

$$\dot{m}_5 = \dot{m}_4 = 0.273 \text{ kg/s}$$

$$T_{5,db} = T_{3,db} = 24^\circ\text{C}$$

$$\omega_5 = \omega_4 = 0.0183 \frac{\text{kg water}}{\text{kg dry air}}$$

$$\dot{Q} = \dot{m}_2 C_p (T_3 - T_2)$$

$$T_2 = T_3 - \frac{\dot{Q}}{\dot{m}_2 C_p}$$

$$T_2 = 24^\circ\text{C} - \frac{21.1 \text{ kW}}{(0.546 \text{ kg/s})(1.005)}$$

$$T_2 = 14.5^\circ\text{C}$$

$$h_1 = \frac{\dot{m}_o h_o + \dot{m}_4 h_4}{\dot{m}_o + \dot{m}_4}$$

$$h_1 = \frac{(0.273)(78.5) + (1.94)(47.5)}{(0.273) + (1.94)}$$

$$h_1 = 51.3 \text{ kJ/kg dry air}$$

$$\dot{m}_2 = \dot{m}_o + \dot{m}_5$$

$$\dot{m}_2 = 2 \cdot \dot{m}_o$$

$$\dot{m}_2 = 2(0.273)$$

$$\dot{m}_2 = 0.546 \text{ kg/s}$$

$$\dot{Q} = \dot{m}_1 C_p (T_3 - T_2)$$

$$21.1 = \dot{m}_1 (1.005) (24 - 14.5)$$

$$\dot{m}_1 = 2.21 \text{ kg/s}$$

$$\dot{m}_4 = \dot{m}_1 - \dot{m}_o$$

$$= 2.21 - 0.273$$

$$= 1.94 \text{ kg/s}$$

$$\omega_1 = \frac{\dot{m}_o \omega_o + \dot{m}_4 \omega_4}{\dot{m}_o + \dot{m}_4}$$

$$\omega_1 = \frac{(0.273)(0.0183) + (1.94)(0.009)}{(0.273) + (1.94)}$$

$$\omega_1 = 0.0101 \frac{\text{kg water}}{\text{kg dry air}}$$

$$a.) \dot{Q} = \dot{m} C_p \Delta T$$

$$\dot{V} = \frac{\dot{Q}}{\rho C_p \Delta T}$$

$$\dot{V} = \frac{\dot{Q}}{\rho C_p (T_1 - T_2)}$$

$$\dot{V} = \frac{21.1 \text{ kW/s}}{\rho C_p (T_1 - T_2)}$$

$$\dot{V} = \frac{21.1 \text{ kW/s}}{1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} (27 - 14.5)}$$

$$\dot{V} = 1.91 \text{ m}^3/\text{s}$$

$$\dot{V} = 1.91 \text{ m}^3/\text{s}$$

$$d.) \dot{Q}_{\text{evap}} = \dot{m}_1 (h_1 - h_2)$$

$$= 2.21 \text{ kg/s} (51.3 \frac{\text{kJ}}{\text{kg}} - 47.5 \frac{\text{kJ}}{\text{kg}})$$

$$\dot{Q}_{\text{evap}} = 8.4 \text{ kW/s} \quad \text{Required capacity of evaporator}$$

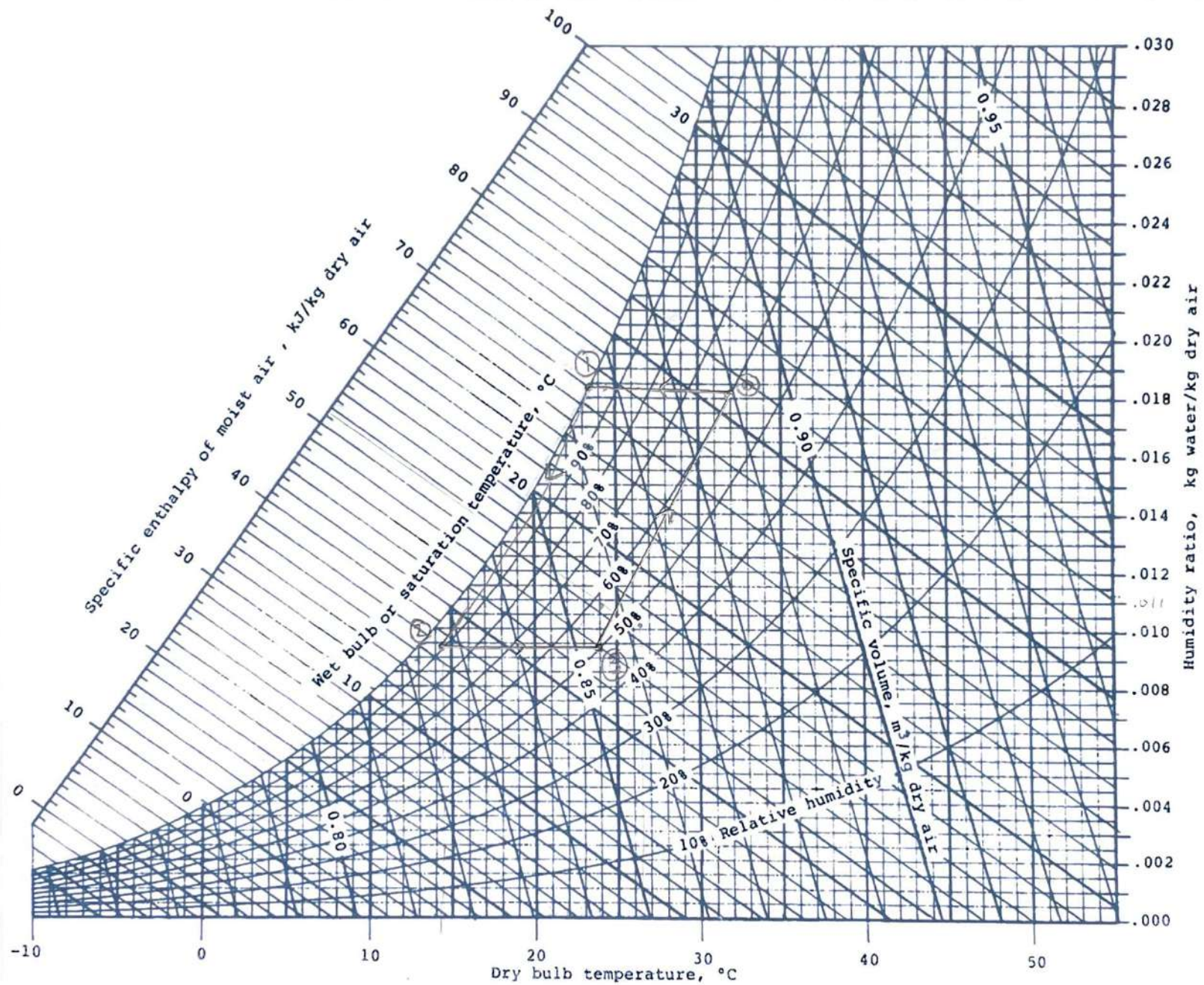
$$e.) \dot{m}_{\text{water}} = \dot{m}_1 (w_1 - w_2)$$

$$= 2.21 (0.0101 - 0.0093)$$

$$\dot{m}_{\text{water drained}} = 0.001768 \text{ kg/s}$$

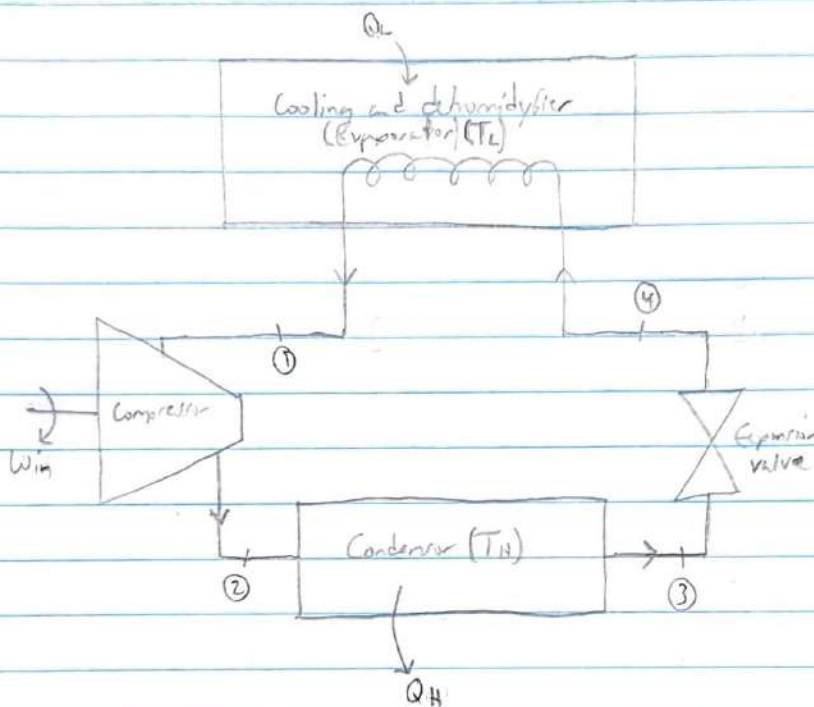
Summary: A conditioned space must be maintained at 75°F (24°C) and 50% relative humidity, with heat gain of 72,000 BTU/hr. There was no moisture created in the space, therefore the humidity ratio remained constant. The system supplied 500 CFM (0.273 kg/s) of fresh outdoor air at 90°F (32°C) with 60% relative humidity, mixed with the return air of the conditioned space.

Analysis: The properties of air at each state was determined using a psychrometric chart which was then used to calculate the mass flow rate and used mass balance equations. The required cooling and dehumidifying capacity of the coil was 8.4 kW/s and the amount of liquid water drained was 0.001768 kg/s. The air is cooling and dehumidifying from states 0 to 2. To maintain the temperature and humidity in the conditioned space, Temperature at 2 needs to be lower than the space.



2.) Purpose: Use cooling and dehumidifier unit from previous problem to solve the operating pressure of the evaporator and the condenser, find the states of the cycle, refrigerant mass flow rate, COP of cycle, power required, and waste heat rate.

Diagrams:



Source: Cengel, Boles, Kanoglu. Thermodynamics: An Engineering Approach, 9th edition. McGraw Hill, 2020.

Design Considerations:

- Steady operating conditions
- Vapor-compression refrigeration cycle

Condenser and Evaporator operate 10° below the surroundings

Data and Variables:

$$Q_L = 8.4 \text{ kW}$$

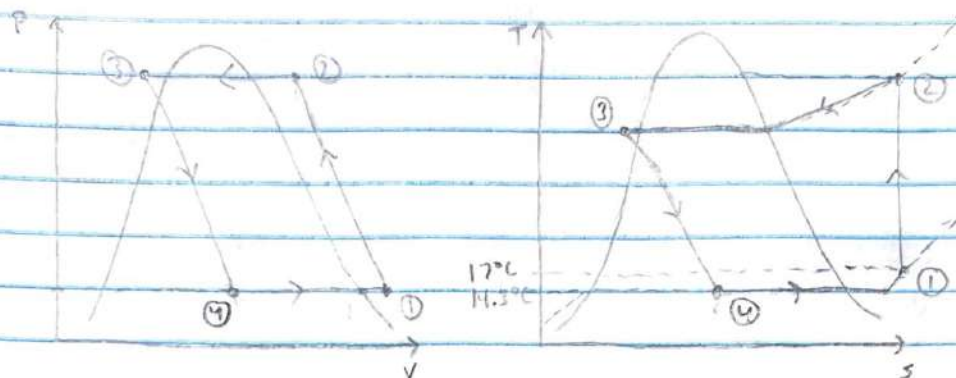
$$\eta_{\text{comp}} = 80\%$$

$$T_1 = \text{Superheated by } 2.7^\circ\text{C}$$

$$T_3 = \text{Subcooled by } 6.3^\circ\text{C}$$

Material: Refrigerant R-134a

Procedure: Determine the states, P-V, and T-s diagrams then solve each problem



The evaporator operates at 10° below the surrounding. From the previous problem the $T_{air, in} = 24.3^\circ\text{C}$, therefore $T_{evap, sat} = 14.3^\circ\text{C}$ and super heated by 2.7°C .

* Interpolations were done using calculator

① Isentropic compression		② P const Condensor		③ Expansion		④ P const		①
$T_1 = 17^\circ\text{C}$	$S_2 = S_1 = 1.2983 \text{ kJ/kg}\cdot\text{K}$	$T_3 = T_2 = 6.3$	$T_4 = 14.3^\circ\text{C}$					
S.H. Table	$h_2 = 552.26 \text{ kJ/kg}$	$T_3 = 35.7$	Table A-11					
$X_1 = 1$	S.H. Table	$P_3 = P_2 = 1072.8 \text{ kPa}$	$P_4 = 477.9 \text{ kPa}$					
$P_1 = 477.9 \text{ kPa}$	$T_2 = T_{outside} + 10^\circ$	$h_3 = 269.39 \text{ kJ/kg}$	$h_{4f} = 71.36 \text{ kJ/kg}$					
$h_1 = 389.11 \text{ kJ/kg}$	$T_2 = 32^\circ\text{C} + 10^\circ = 42^\circ\text{C}$		$h_{4g} = 258.51 \text{ kJ/kg}$					
$S_1 = 1.2983 \text{ kJ/kg}\cdot\text{K}$	$P_2 = 1072.8 \text{ kPa}$		$h_{4f,g} = 187.29 \text{ kJ/kg}$					
	$h_{2s} = 258.51 \text{ kJ/kg}$		$x = \frac{h_g - h_c}{h_{fg}} = \frac{187.15}{187.29} = 0.99$					

$$\eta_{comp} = \frac{h_1 - h_{2s}}{h_1 - h_2}$$

$$.80 = \frac{389.11 - 258.59}{389.11 - h_2}$$

$$h_2 = 389.11 + \frac{130.52}{.80}$$

$$h_2 = 552.26 \text{ kJ/kg}$$

a.) Condenser $P = 477.9 \text{ kPa}$

Evaporator $P = 1072.8 \text{ kPa}$

$$e.) \dot{m} = \frac{\dot{Q}}{h_1 - h_4}$$

$$= \frac{8.4 \text{ kW}}{389.11 \frac{\text{kJ}}{\text{kg}} - 258.51 \frac{\text{kJ}}{\text{kg}}}$$

$$\dot{m} = 0.064 \text{ kg/s}$$

$$d.) \dot{W}_{in} = \dot{m}(h_2 - h_1)$$

$$= 0.064(552.26 - 389.11)$$

$$\dot{W}_{in} = 10.44 \text{ kW}$$

$$COP = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{(h_1 - h_4)}{10.44} = \frac{389.11 - 258.51}{10.44} = 12.51$$

$$f.) \dot{W}_{in} = 10.44 \text{ kW} \times 1.341 = 14 \text{ hp}$$

$$g.) \dot{Q}_{waste} = \dot{m}(h_2 - h_3)$$

$$= 0.064(552.26 - 269.79)$$

$$\dot{Q}_{waste} = 18 \text{ kW}$$

Summary: This design uses data calculated in the previous problem. It is a vapor-compression cycle using refrigerant R-134a, where the refrigerant exits the evaporator by 2.7°C and leaves compressor superheated by 6.3°C . As we learned in class, the evaporator and condenser operate with a 10° difference from its surrounding.

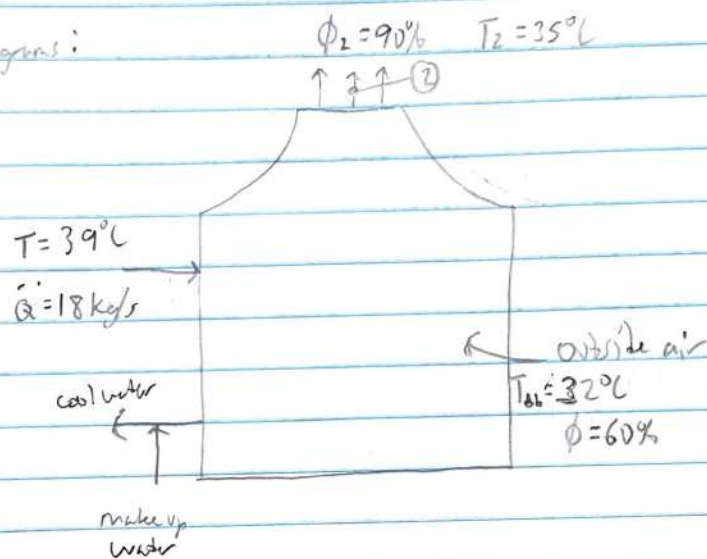
Analysis: The properties at each state were determined using the refrigerant tables A-11 and A-13 which were then used to calculate required mass flow, compressor power, COP, and waste heat rate. From the previous problem the required capacity of the evaporator was calculated, however if that value was incorrect that could lead to problem 2 values to be incorrect. Also,

I found that the mass flow rate of the refrigerant was low,
 $\dot{m} = 0.067 \text{ kg/s}$, which could be an error in my calculations.

3.) Bonus

Purpose: To revise the vapor-compression refrigeration cycle design to absorb the waste water using a cooling tower and provide volume flow rate and mass flow rate of makeup water.

Diagrams:



Source: Cengel, Boles, Kengli. Thermodynamics. An Engineering Approach.
9th edition, McGraw Hill, 2020.

Design Considerations:

- Steady operating conditions
- Ideal gas

Data and Variables:

$$\text{From problem 2: } T = \frac{T_2 + T_3}{2} = \frac{42 + 35.2}{2} = 39^\circ\text{C}$$

$$\dot{Q}_{\text{water}} = 18 \text{ kW}$$

$$c_{p,\text{water}} = 4.18 \text{ kJ/kg}\cdot\text{K}$$

$$\phi = 90\%$$

$$\Delta T = 3^\circ\text{F} = 1.67^\circ\text{C}$$

$$\rho_{\text{air}} = 1.2 \text{ kg/m}^3 \text{ at } 20^\circ\text{C}$$

Materials: Air

Procedure: Calculate volume flow rate of outside air and then mass flow rate of makeup water.

$$a.) \dot{Q}_{\text{cool}} = \dot{m}_w c_p \Delta T$$

$$\dot{m}_w = \frac{\dot{Q}_{\text{cool}}}{c_p \Delta T} = \frac{18 \text{ kJ/s}}{(4.18 \text{ kJ/kg}\cdot\text{K})(1.67)} = 2.58 \text{ kg/s}$$

$$\dot{V}_{\text{air}} = \frac{\dot{m}}{\rho_{\text{air}}} = \frac{2.58 \text{ kg/s}}{1.2 \text{ kg/m}^3} = 2.15 \text{ m}^3/\text{s}$$

b.) Air leaves ϕ 90%, $T = 35^\circ\text{C}$

$$w_1 = 0.0101 \text{ (from problem 1)}$$

$$w_2 = 0.622 \cdot \frac{P_v}{P - P_v}$$

$$P_v = 0.90 \cdot P_{\text{sat}}$$

$$P_{\text{sat}@35^\circ\text{C}} = 5.6291 \text{ kPa}$$

$$P_v = 0.90(5.6291) = 5.0662 \text{ kPa}$$

(Table A-9)

$$w_2 = 0.622 \cdot \frac{5.0662}{101 - 5.0662} = 0.0328 \text{ kg water/kg air}$$

$$\dot{m}_{\text{makeup}} = \dot{m}_w (w_2 - w_1) = 2.58(0.0328 - 0.0101) = 0.0586 \text{ kg/s}$$

Summary: The cooling tower is designed to remove waste heat from the condenser of the refrigeration cycle. To replace the water, makeup water is added in the tower.

Analysis: The required air flow rate is calculated at $2.15 \text{ m}^3/\text{s}$ based on the heat rejection with 3°F change in temperature. The makeup flow rate is 0.0586 kg/s . These values are based off of the calculate heat rejection of 18 kJ/s in the previous problem.