Cooling Tower: Part I

Thermal, Fluids, and Energy Systems Lab

(ME EN 4650)

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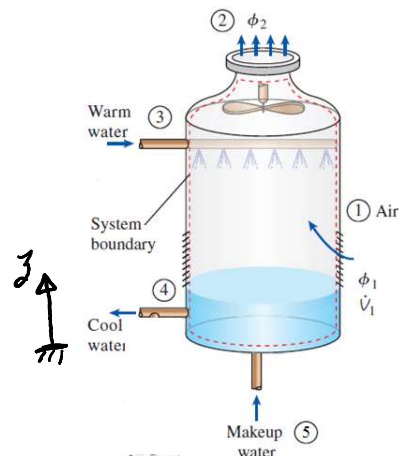
1

2

Cooling Tower Performance

What we want to know:

- → T_{db}, T_{wb}, T_w vs z
- → efficiency, η vs $\dot{m}_{w_{in}}$
- → $\dot{m}_{w_{out}}$
- → $\dot{Q}$, heat rejected



What we can measure:

- → T_{db}, T_{wb}, T_w vs. z (thermocouples)
- → ΔP (orifice plate) → $\dot{m}_a$
- → $\dot{m}_{w_{in}}$ (rotameter)

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2

Lecture Outline

- Background
- Experimental Setup
- Measurements and Instrumentation
- Required Figures
- Data Analysis

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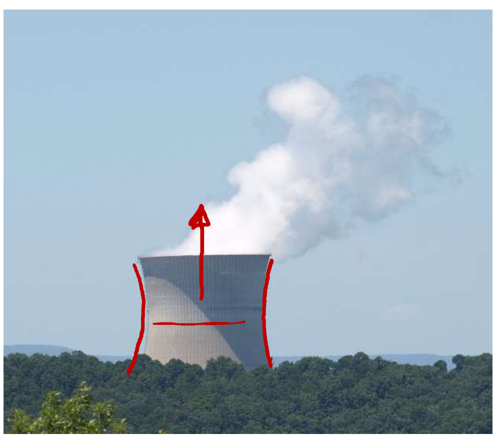
Hyperboloid Cooling Towers



Rectangular Cooling Towers

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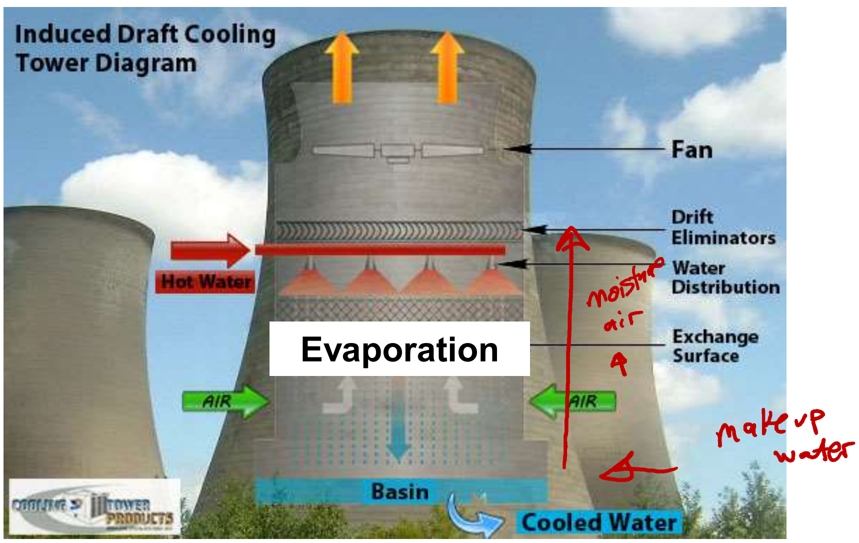
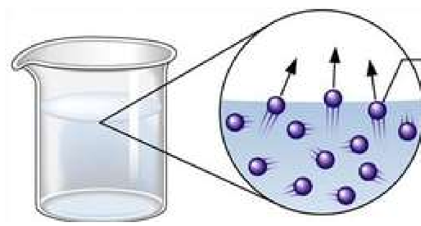
5

Induced Draft Counterflow Cooling Tower



latent heat of vaporization

Evaporation



@ room temp,
$P_v = 2.4$ kPa
$P_g = 2.84$ kPa

Evaporation criterion: $\underbrace{P_v}_{\text{vapor pressure of water}} < \underbrace{P_g}_{\text{saturation pressure of liquid water}}$

➢ Evaporation will ALWAYS occur at room temperature, as long as air is NOT saturated.

Rate of heat rejected: $Q_e = \dot{m}_e \, h_e \approx 1$ kW

$\dot{m}_e$: 0.4 g/s
h_e: 2256 kJ/kg

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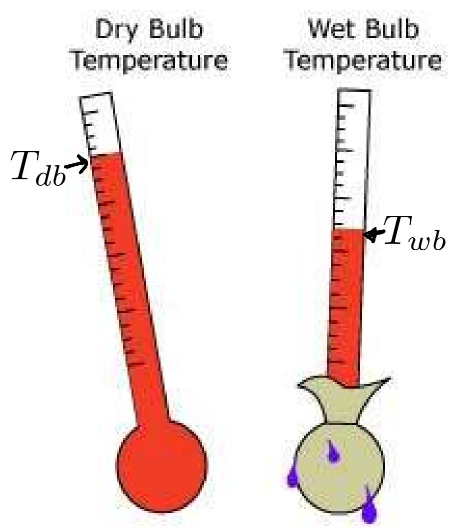
7

Wet-Bulb Temperature



$$T_{wb} \leq T_{db}$$

Psychrometric chart

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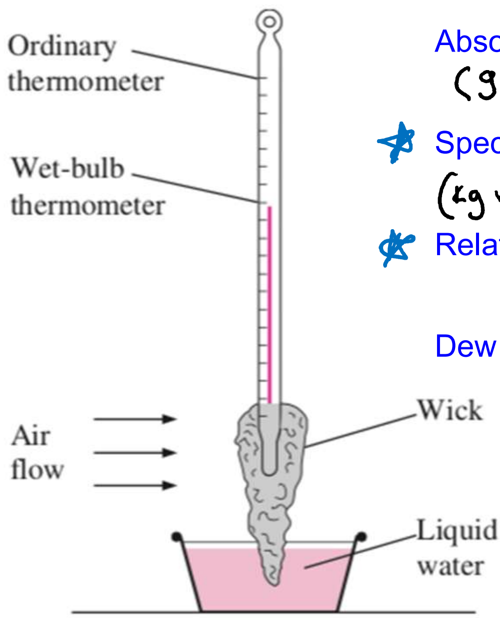
8

Wet-Bulb TemperatureMeasuring Water Vapor Content in Air



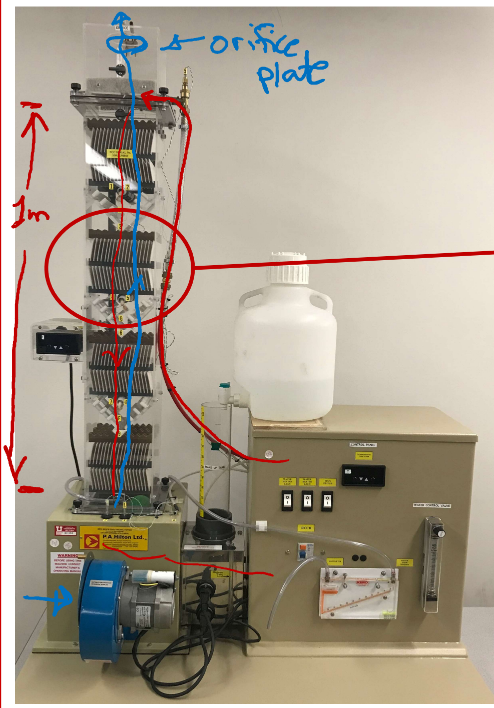
Absolute Humidity: mass water vapor per unit volume of air
(g w.v./cm^3 air)

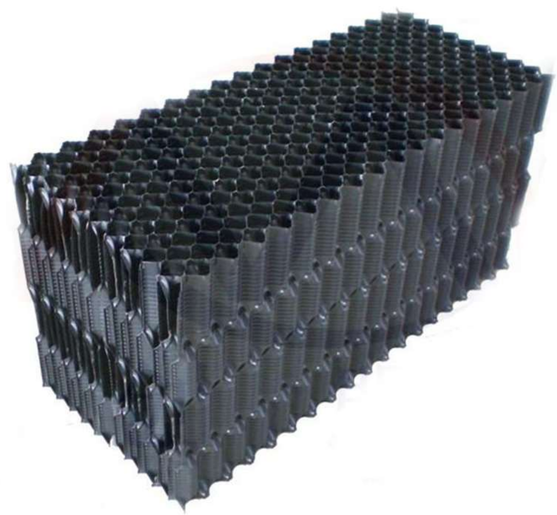
Specific Humidity, ω : mass of water vapor per unit mass of dry air
(kg w.v./kg dry air)

Relative Humidity, ϕ : absolute humidity over max allowable
(%)

Dew Point Temperature: temp @ which air must be cooled to be sat. w/ w.v.
(°C)

Experimental Setup





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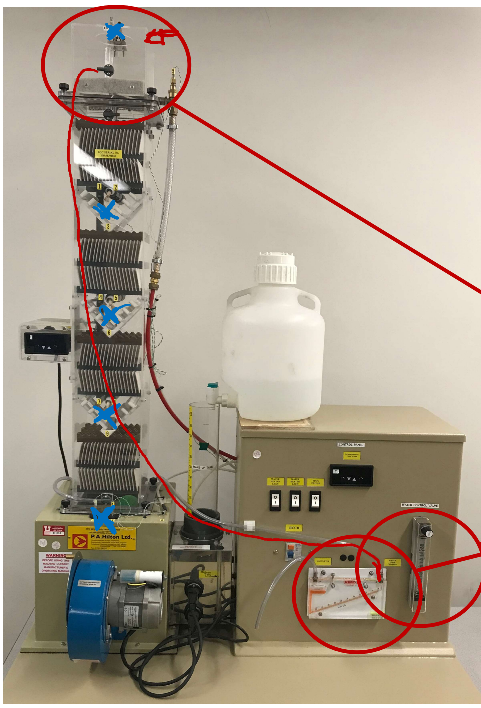
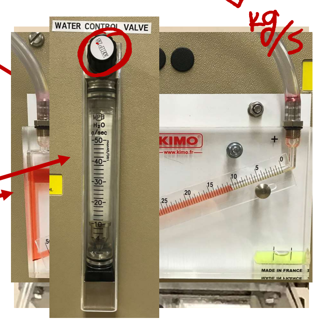
10

Measurements



Quantity	Symbol	Units	Instrument
Dry bulb temperature	T_{db}	°C	thermocouple
Wet bulb temperature	T_{wb}	°C	thermocouple with wet cloth
Water temperature	T_w	°C	thermocouple
Orifice meter pressure drop	ΔP	mm H_2O	inclined manometer
Inlet water flow rate	$\dot{m}_{w_{in}}$	g/s	rotameter

kg/s



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11

Experiments

Quantity	Symbol	Units	Instrument
Dry bulb temperature	T_{db}	°C	thermocouple
Wet bulb temperature	T_{wb}	°C	thermocouple with wet cloth
Water temperature	T_w	°C	thermocouple
Orifice meter pressure drop	ΔP	mm H_2O	inclined manometer
Inlet water flow rate	$\dot{m}_{w_{in}}$	g/s	rotameter

Exp	$\dot{m}_{w_{in}}$ (g/s)
1	30
2	20
3	40

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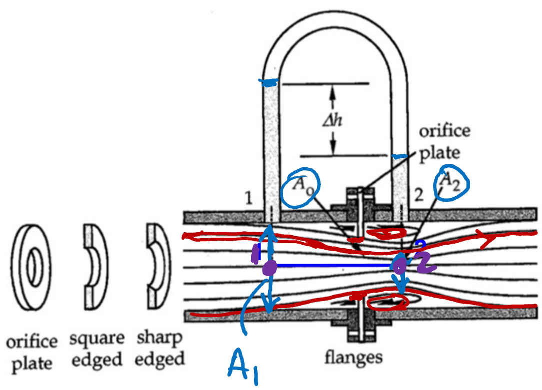
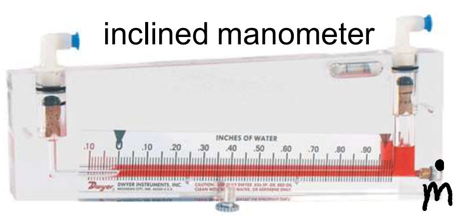
12

Air Flow Rate Measurement:
Sharp-Edged Orifice Meter



inclined manometer



Conservation of mass:

$$\rho A_1 V_1 = \rho A_2 V_2$$

$$V_1 = \frac{A_2}{A_1} V_2$$

Bernoulli's equation:

$$\frac{P_1}{\rho} + \frac{1}{2} V_1^2 = \frac{P_2}{\rho} + \frac{1}{2} V_2^2$$

$$\frac{P_1}{\rho} + \frac{1}{2}\left(\frac{A_2}{A_1}\right)^2 V_2^2 = \frac{P_2}{\rho} + \frac{1}{2} V_2^2$$

$$V_2 = \sqrt{\frac{(P_1 - P_2)}{\rho}\left[\frac{1}{2} - \left(\frac{A_2}{A_1}\right)^2\right]^{-1}}$$

$$V_2 = \tilde{A}\sqrt{\Delta P/\rho}\quad , \quad \Delta P = P_1 - P_2$$

$$\dot{m} = \rho A_2 V_2 = \rho A_2 \tilde{A}\sqrt{\Delta P/\rho} = C\sqrt{\rho \Delta P}$$

discharge coeff.

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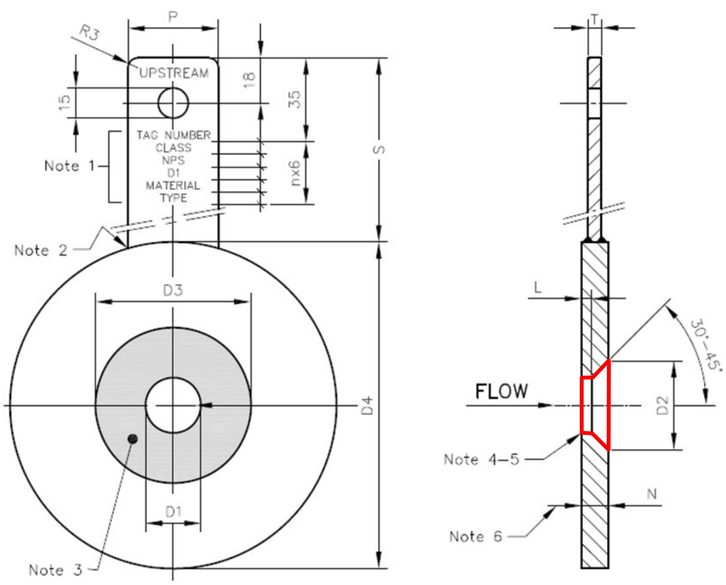
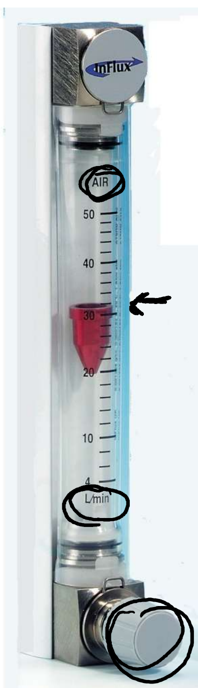
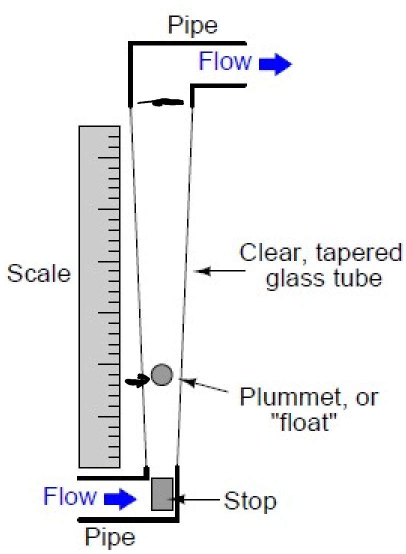
13

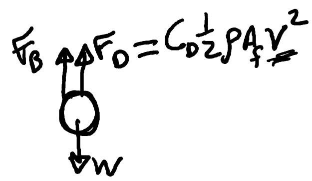
Orifice Plate

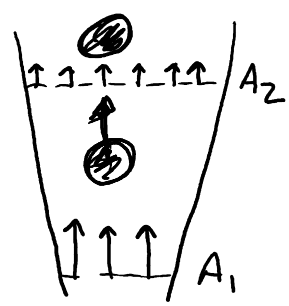


Water Flow Rate Measurement: Rotameter









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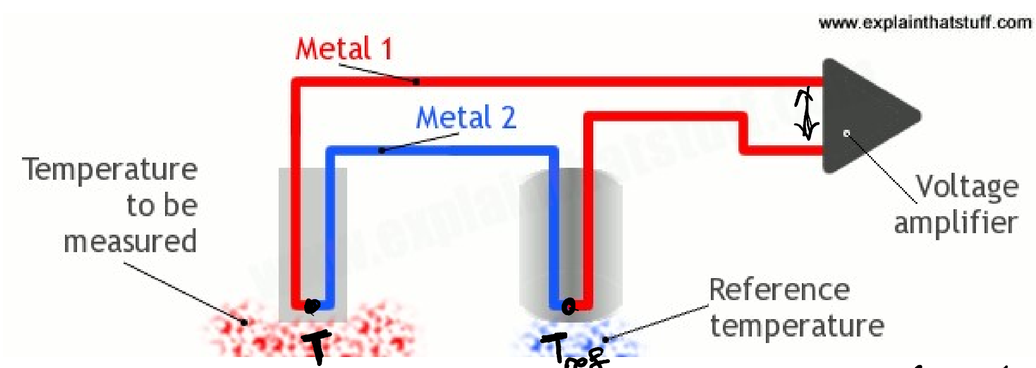
15

Thermocouple: Principle of Operation

Seebeck Voltage



Cold-junction compensation

LM35

$$50 \frac{\mu V}{^\circ C} = \frac{50\times10^{-6} V}{^\circ C}$$

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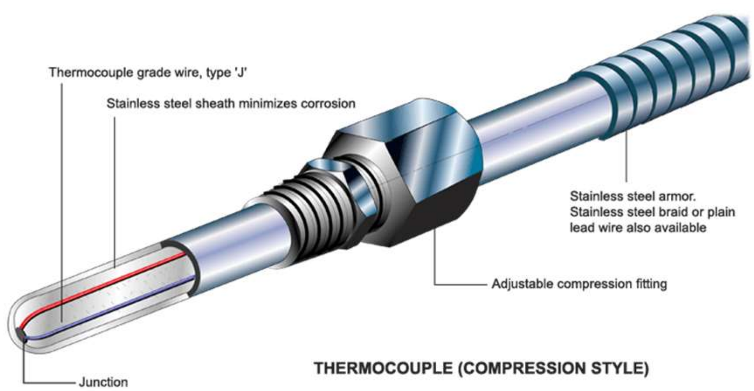
Thermocouple: Probe Type



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17

Thermocouple Application

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18

Thermocouple: Wire Type

THERMOCOUPLE CHARACTERISTICS TABLE

ANSI/ASTM	Symbol Single	Generic Names	Color Coding: Individual Conductor	Color Coding: Overall Jacket Extension Grade Wire	Magnetic Yes/No	Environment (Bare Wire)
T	TP TN	Copper Constantan, Nominal Composition: 55% Cu, 45% Ni	Blue Red	Blue	No No	Mild Oxidizing, Reducing. Vacuum or Inert. Good where moisture is present.
J	JP JN	Iron Constantan, Nominal Composition: 55% Cu, 45% Ni	White Red	Black	Yes No	Reducing Vacuum, Inert. Limited use in oxidizing at High Temperatures. Not recommended for low temps.
E	EP EN	Chromel®, Nominal Composition: 90% Ni, 10% Cr Constantan, Nominal Composition: 55% Cu, 45% Ni	Purple Red	Purple	No No	Oxidizing or Inert. Limited use in Vacuum or Reducing.
K	KP KN	Chromel, Nominal Composition: 90% Ni, 10% Cr Alumel®, Nominal Composition: 95% Ni, 2% Mn, 2% Al	Yellow Red	Yellow	No Yes	Clean Oxidizing and Inert. Limited use in Vacuum or Reducing
N	NP NN	Nicrosil®, Nominal Compositions: 84.6% Ni, 14.2% Cr, 1.4% Si Nisil®, Nominal Composition: 95.5% Ni, 4.4% Si, 1% Mg	Orange Red	Orange	No No	Clean Oxidizing and Inert. Limited use in Vacuum or Reducing
S	SP SN	Platinum 10% Rhodium Pure Platinum	Black Red	Green	No No	Oxidizing or Inert Atmospheres. Do not insert in metal tubes. Beware of contamination.
R	RP RN	Platinum 13% Rhodium Pure Platinum	Black Red	Green	No No	Oxidizing or Inert Atmospheres. Do not insert in metal tubes. Beware of contamination.
B	BP BN	Platinum 30% Rhodium Platinum 6% Rhodium	Gray Red	Gray	No No	Oxidizing or Inert Atmospheres. Do not insert in metal tubes. Beware of contamination.
C*	P N	Tungsten 5% Rhenium Tungsten 26% Rhenium	Green Red	Red	No No	Vacuum, Inert, Hydrogen Atmospheres. Beware of Embrittlement.

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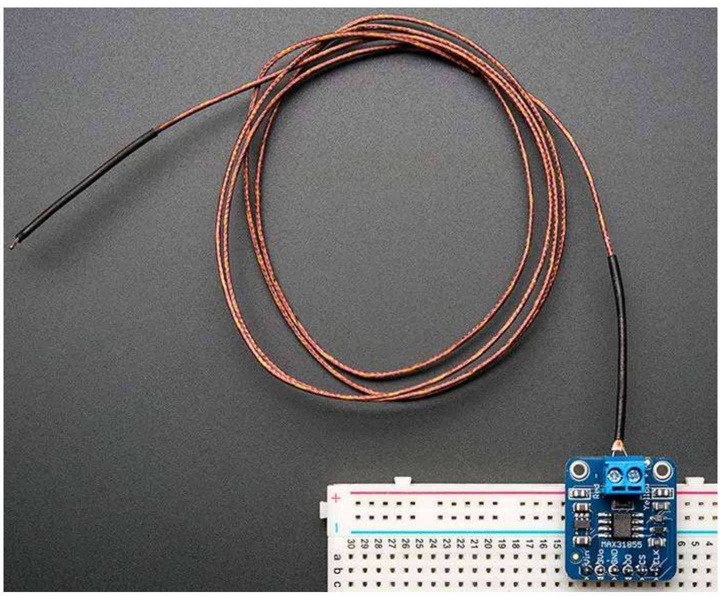
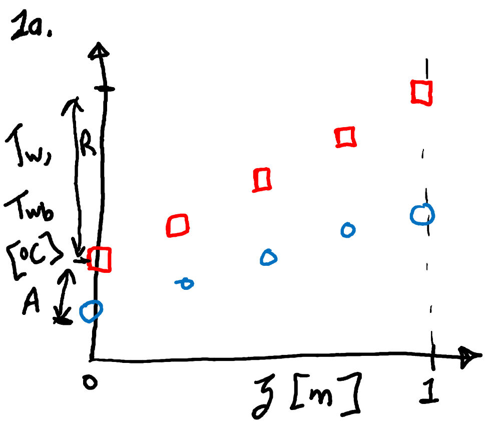
19

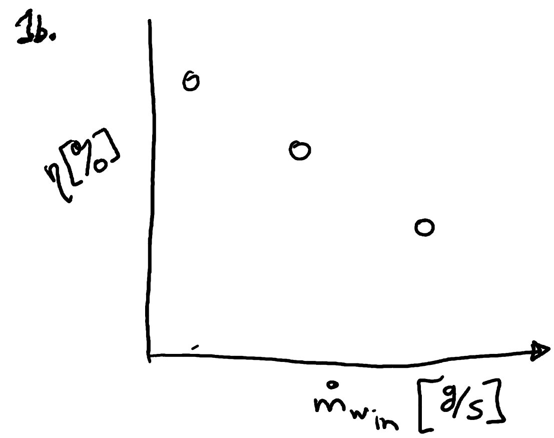
Thermocouple Breakout Board for Arduino



21

Figures 1a & 1b





Range: $R = Tw_{in} - Tw_{out}$

Approach: $A = Tw_{out} - Twb_{in}$

$$\eta = \frac{R}{R+A} * 100$$

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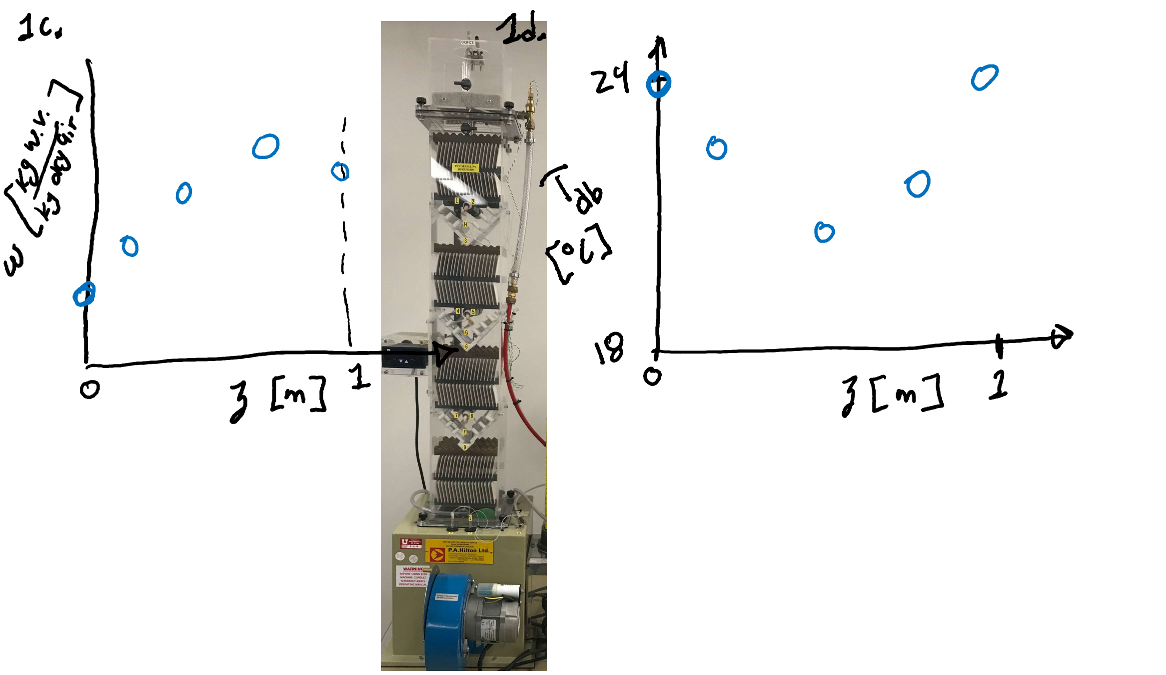
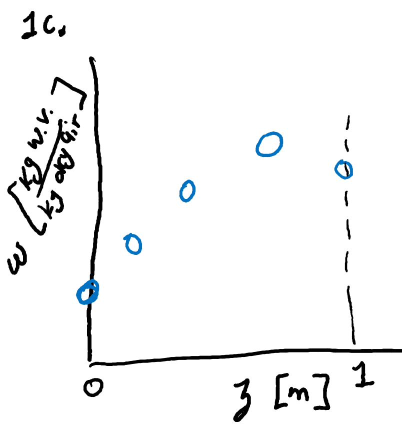
21

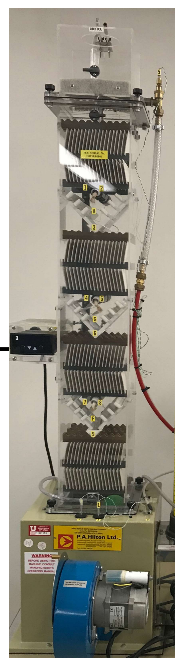
Figures 1c & 1d

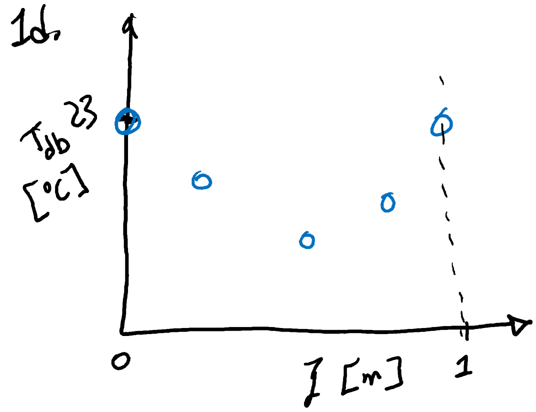


23

Figures 1c & 1d







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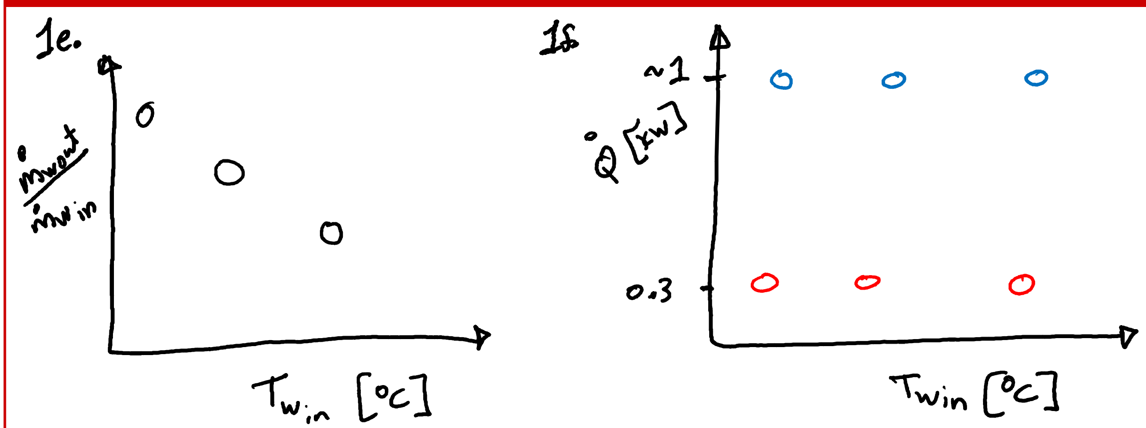
23

24

Figures 1e & 1f



Cooling Tower: Part II

Thermal, Fluids, and Energy Systems Lab

(ME EN 4650)

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University of Utah

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25

Quantities of Interest (Required Figures)

- T_w and T_{wb} vs z
- η vs $\dot{m}_{w_\text{in}}$
- ω vs z
- T_{db} vs z
- $\dot{m}_{w_\text{out}}/\dot{m}_{w_\text{in}}$ vs T_{w_in}
- $\dot{Q}_\text{a}$ and $\dot{Q}_\text{amb}$ vs T_{w_in}

$R = T_{w_{in}} - T_{w_{out}}$

$A = T_{w_{out}} - T_{wb_{in}}$

$\eta = \frac{R}{R+A} \cdot 100$

specific humidity
"psychrometric chart"

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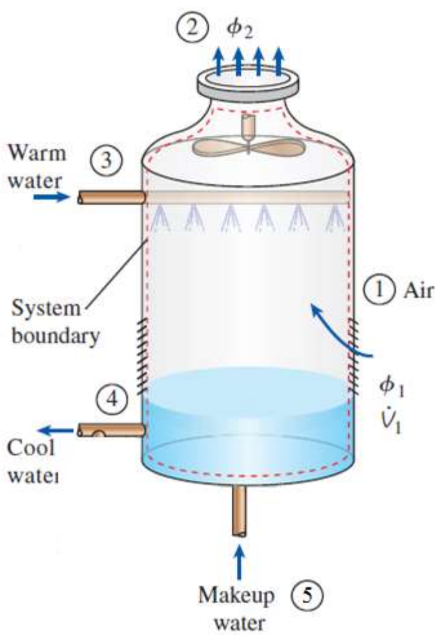
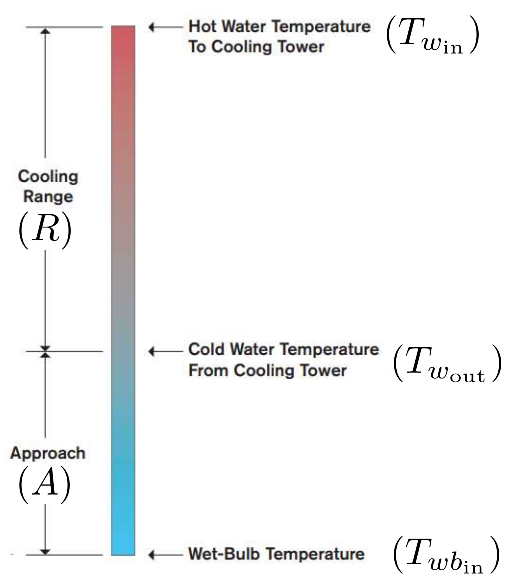
26

Cooling Tower Efficiency





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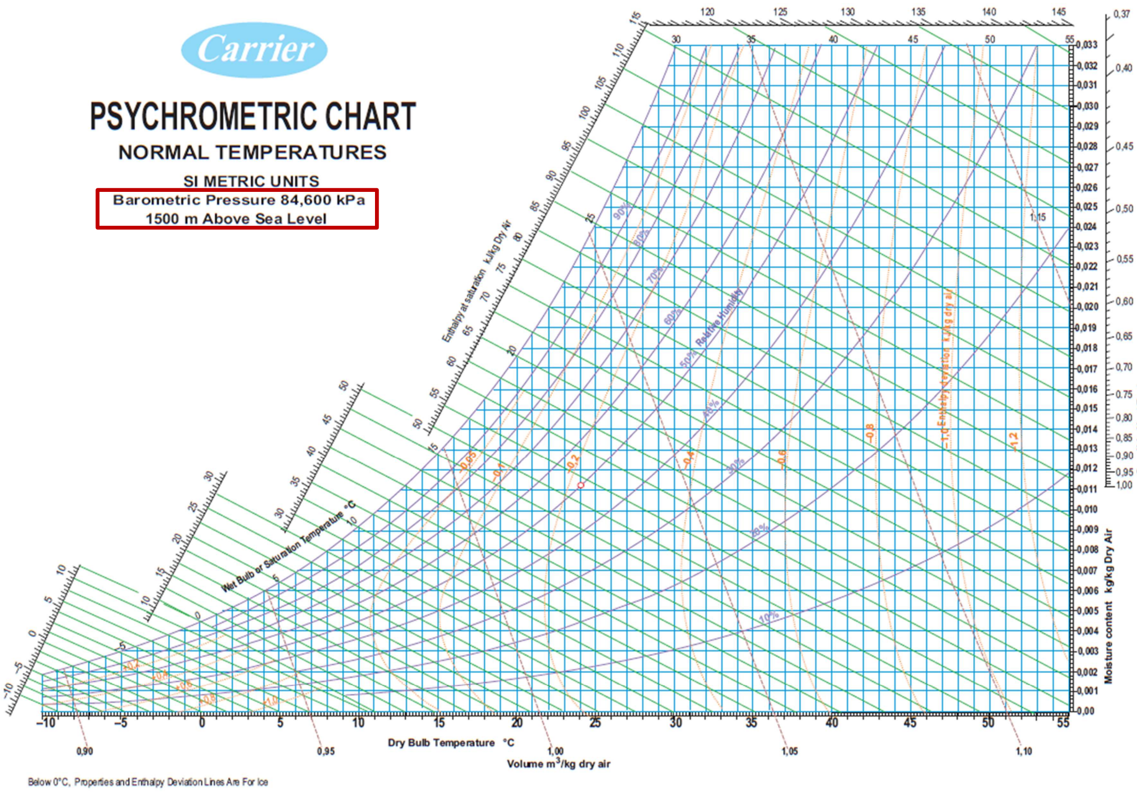
27

Given: $T_{db} = 25°\text{C}$, $T_{wb} = 20°\text{C}$

Find: RH, ω, v, h



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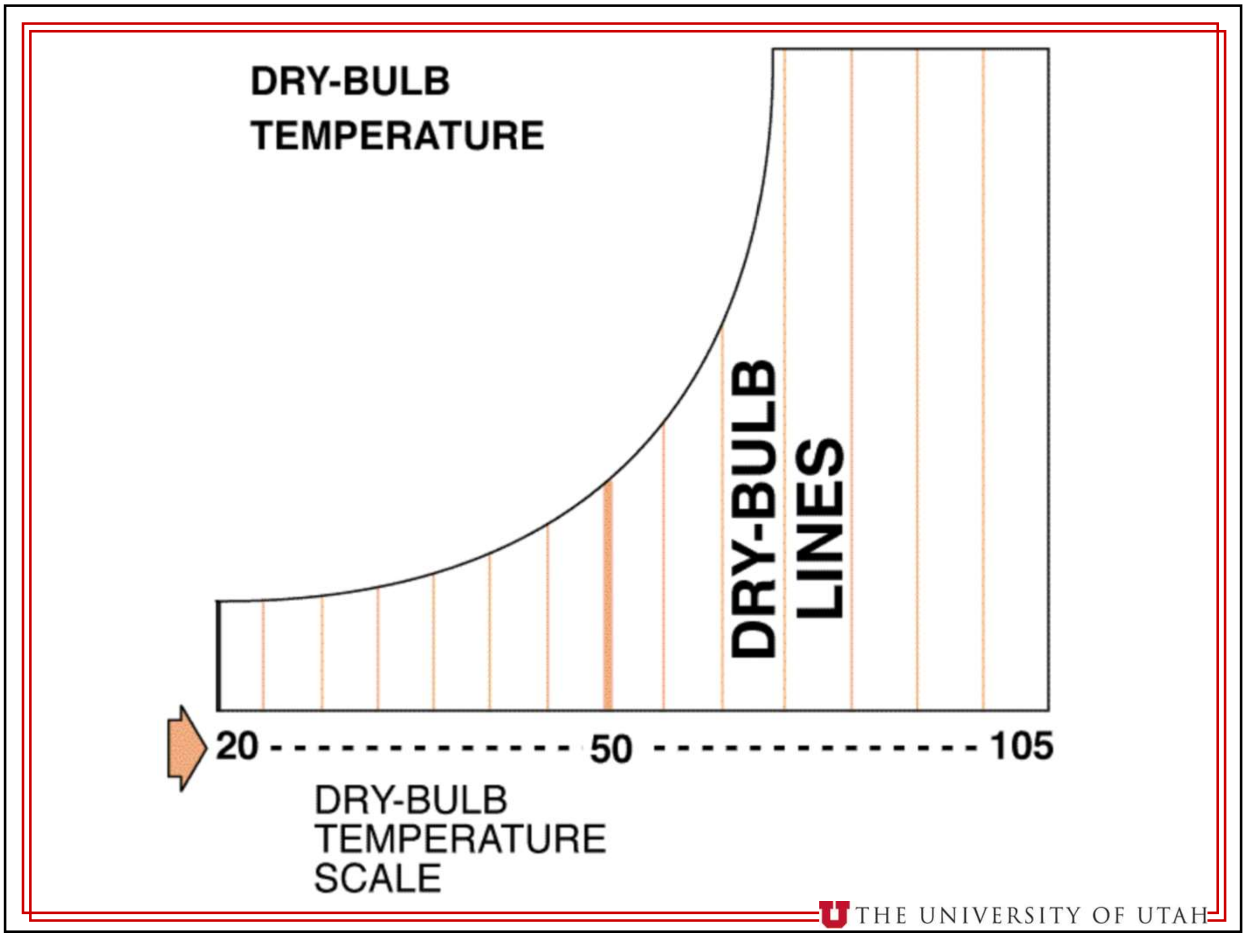
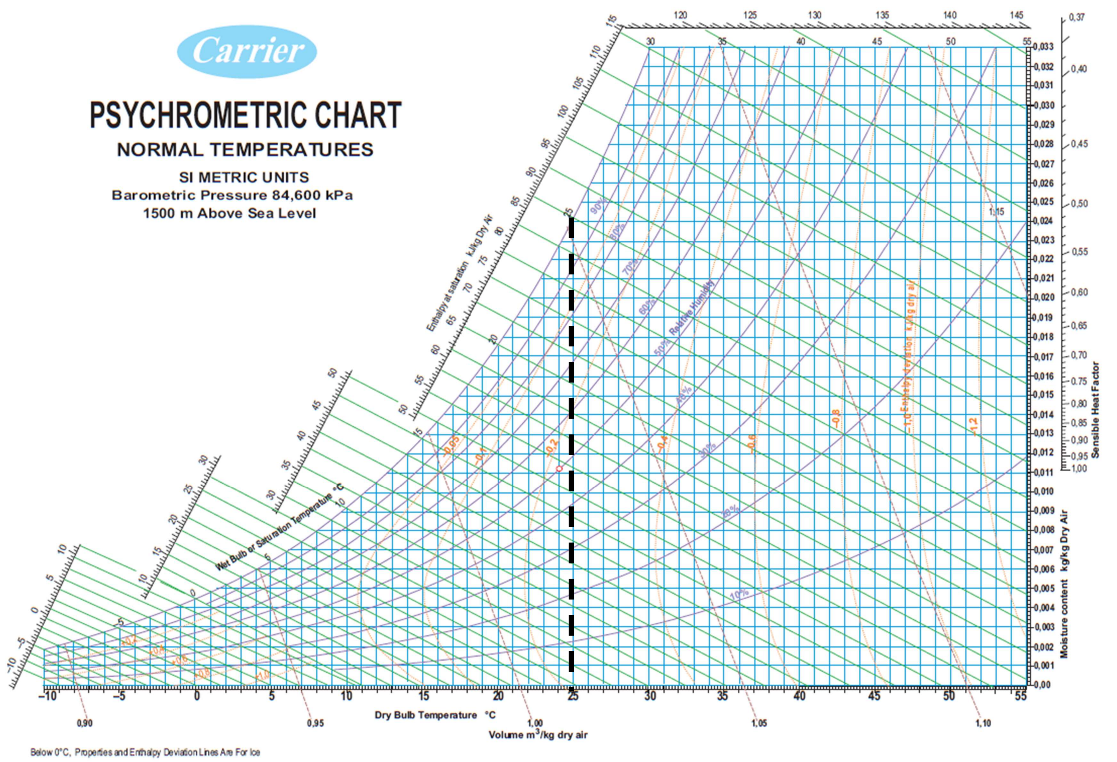

DRY-BULB
TEMPERATURE
DRY-BULB
LINES
20
50
105
DRY-BULB
TEMPERATURE
SCALE
THE UNIVERSITY OF UTAH

29

Given: $T_{db} = 25°C$, $T_{wb} = 20°C$ Find: RH, ω, v, h



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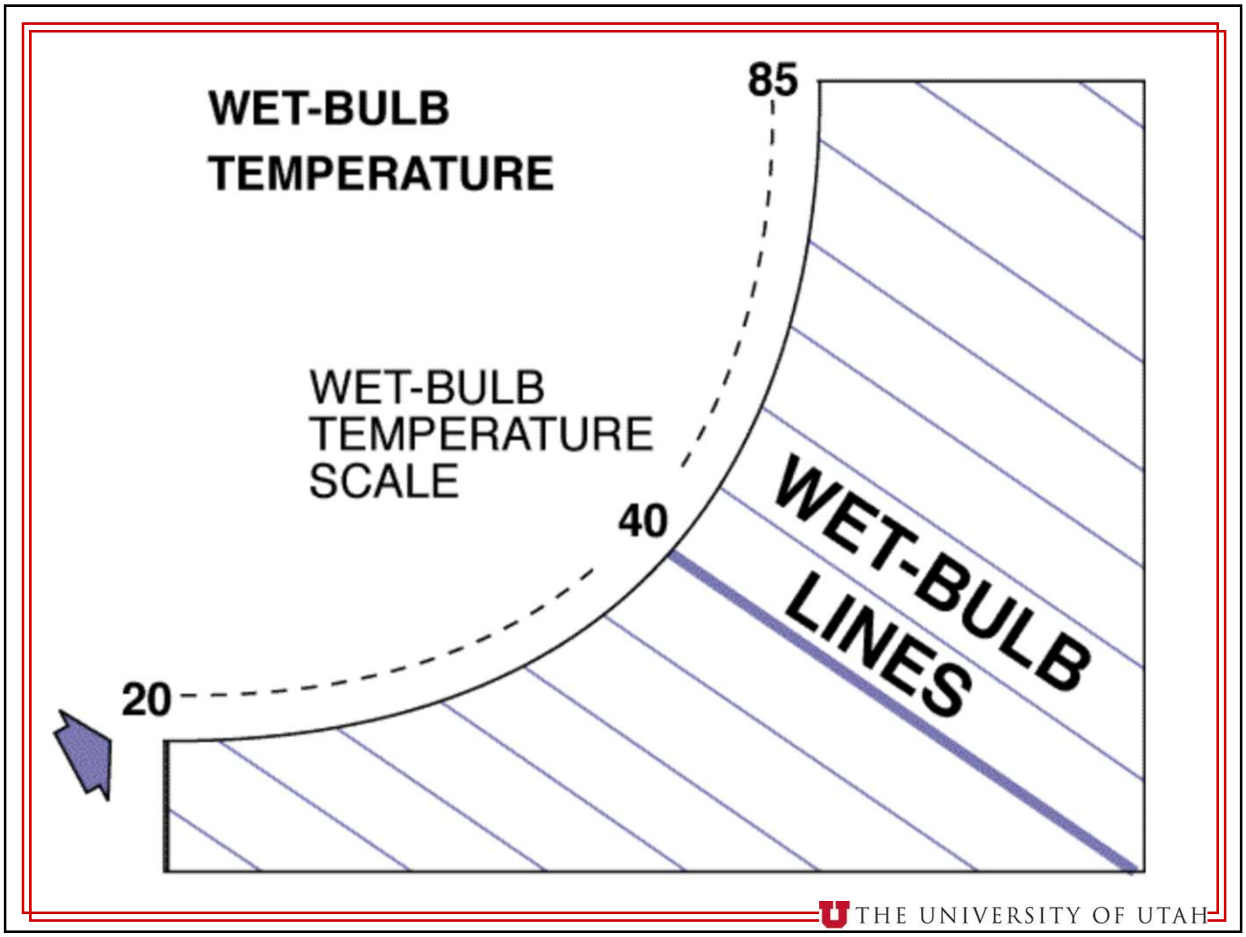
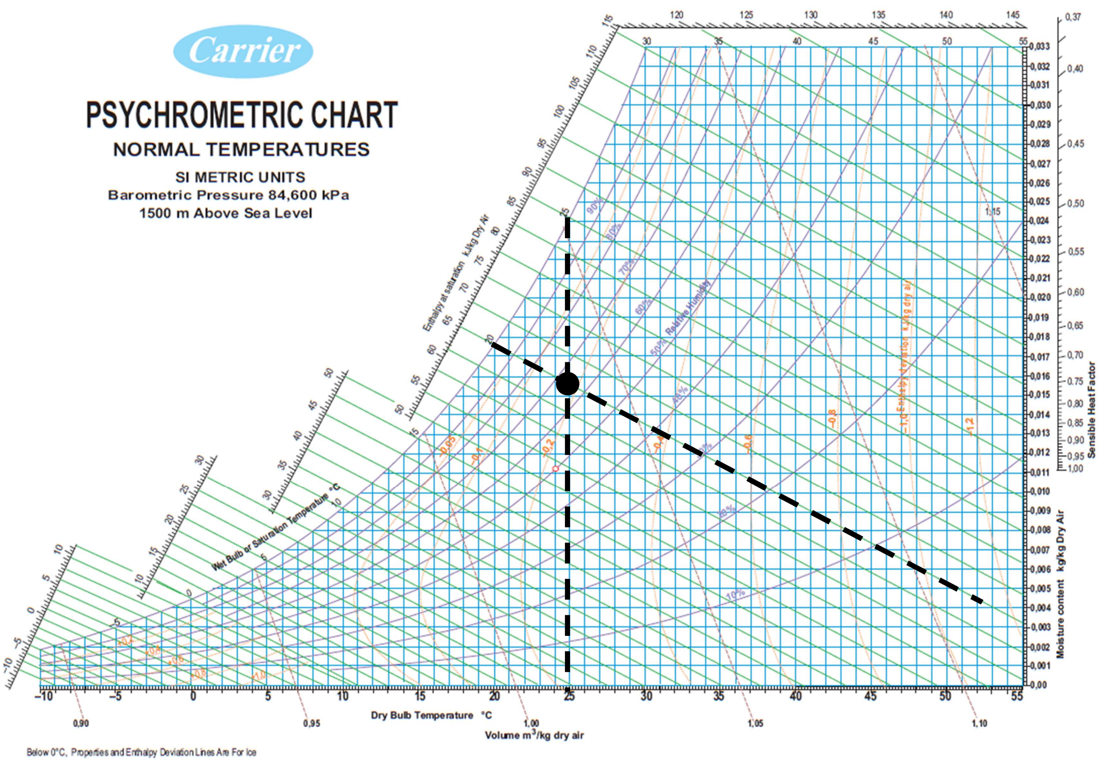
30


WET-BULB
TEMPERATURE
85
WET-BULB
TEMPERATURE
SCALE
40
20
WET-BULB
LINES
THE UNIVERSITY OF UTAH

Given: $T_{db} = 25°C$, $T_{wb} = 20°C$ Find: RH, ω, v, h



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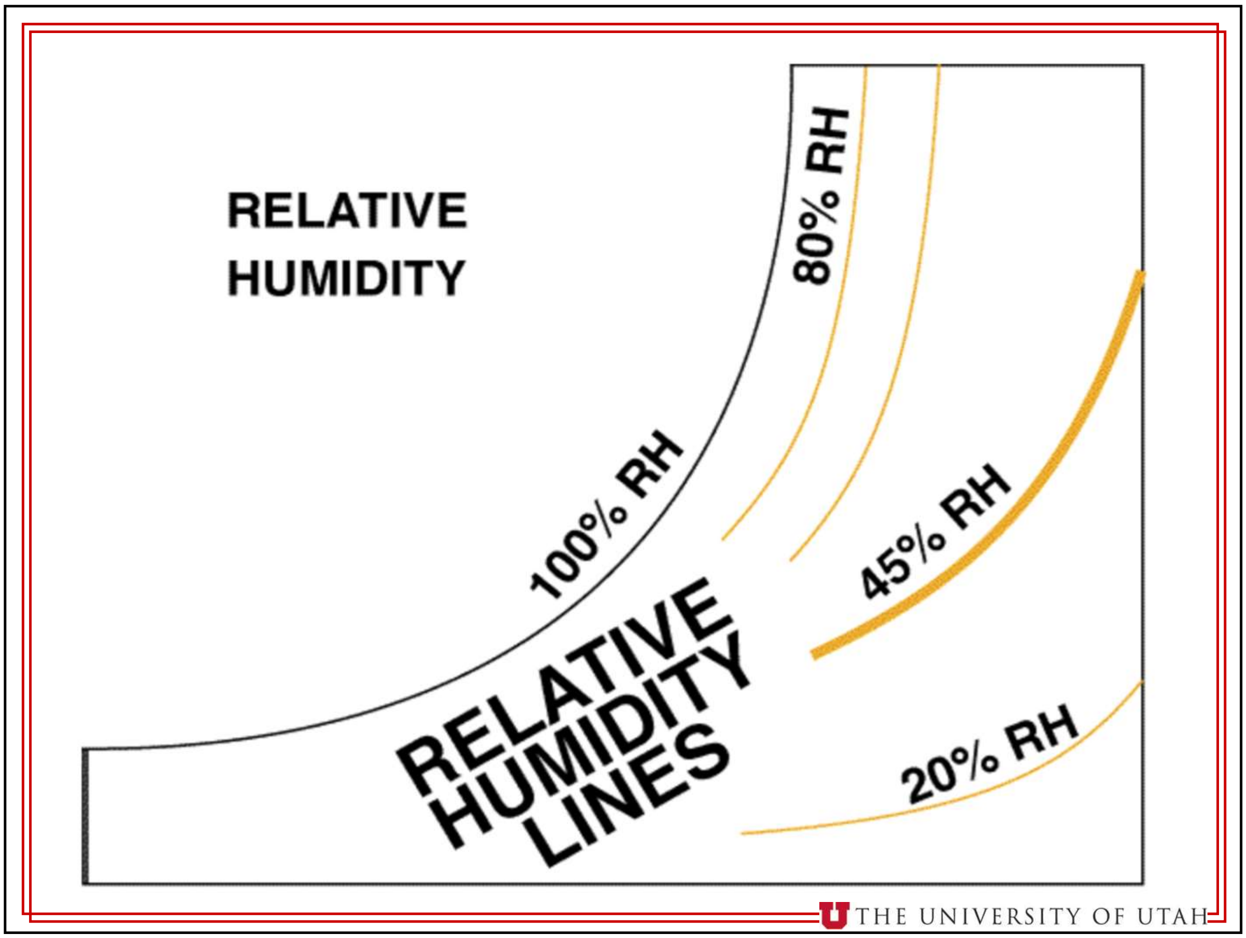
32


RELATIVE
HUMIDITY
80% RH
100% RH
45% RH
RELATIVE
HUMIDITY
LINES
20% RH
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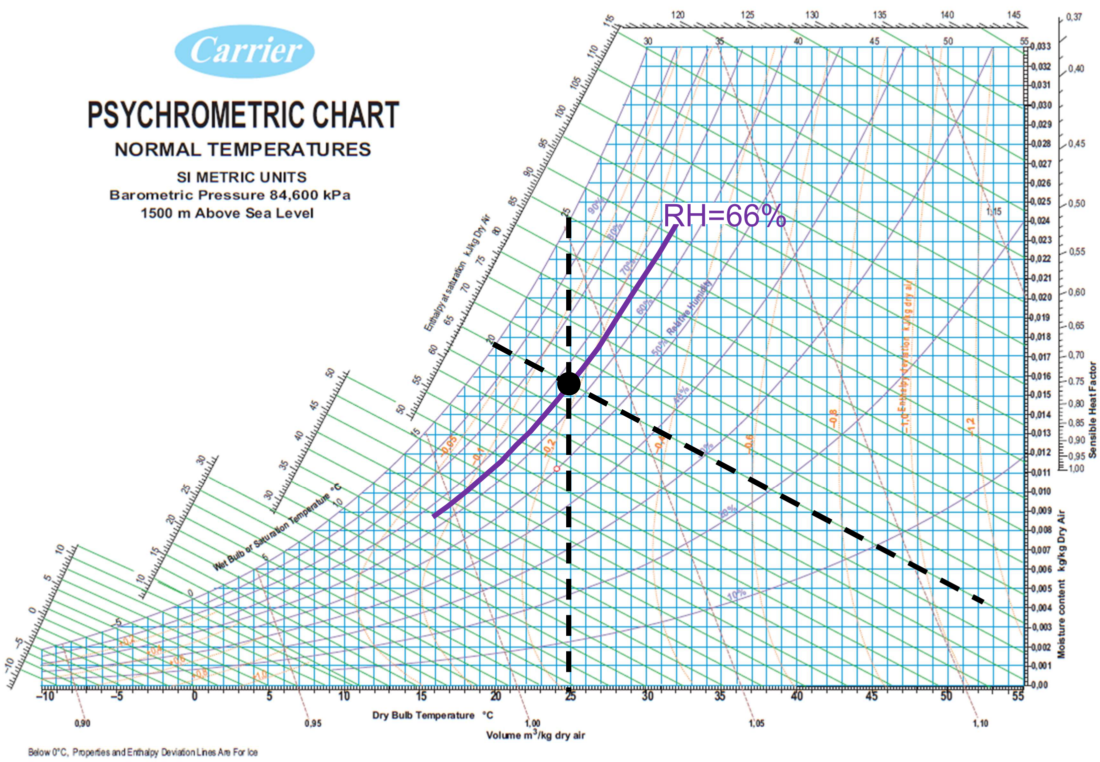
33

Given: $T_{db} = 25°\text{C}$, $T_{wb} = 20°\text{C}$ Find: RH, ω, v, h



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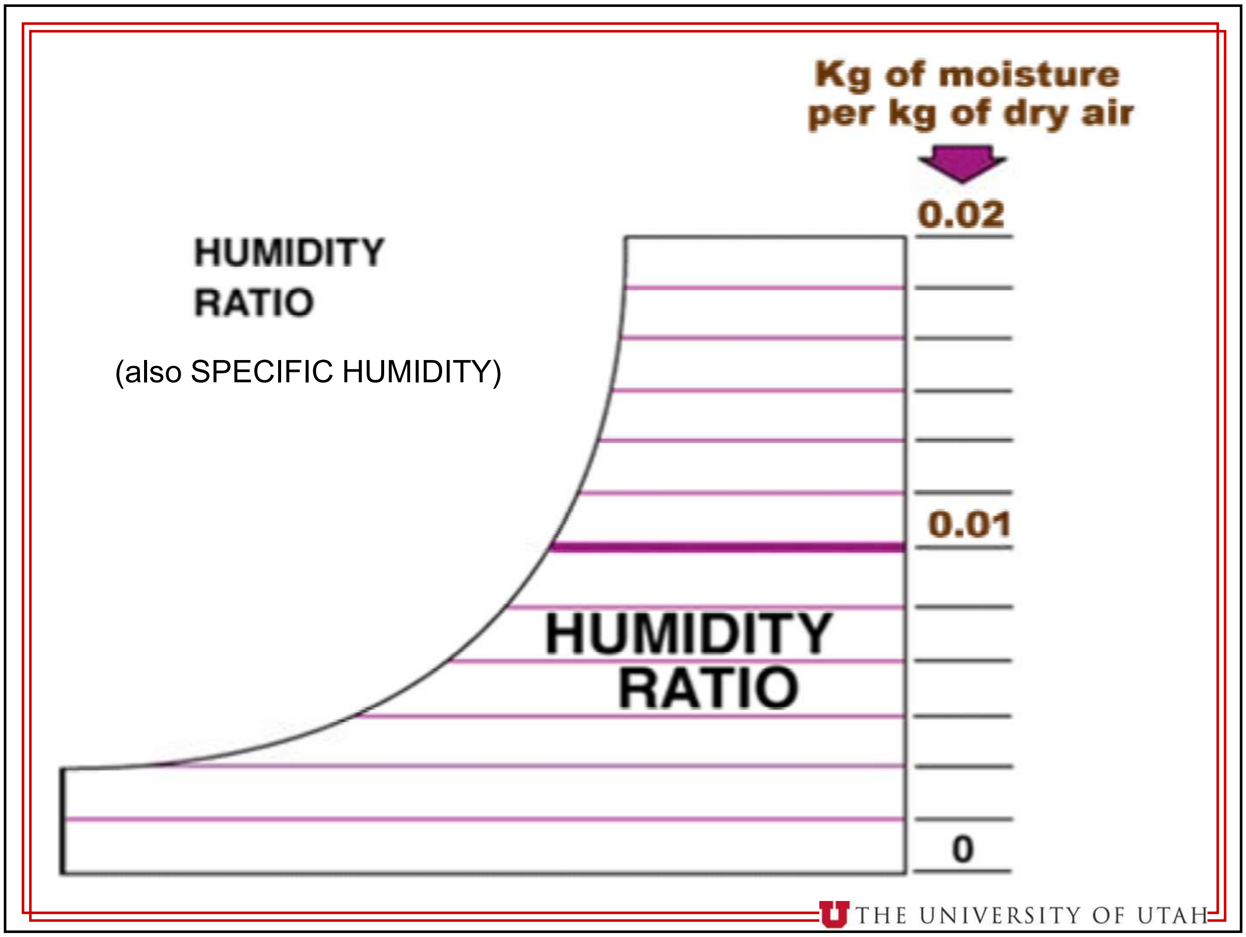
34


Kg of moisture per kg of dry air
0.02
HUMIDITY RATIO
(also SPECIFIC HUMIDITY)
0.01
HUMIDITY RATIO
0
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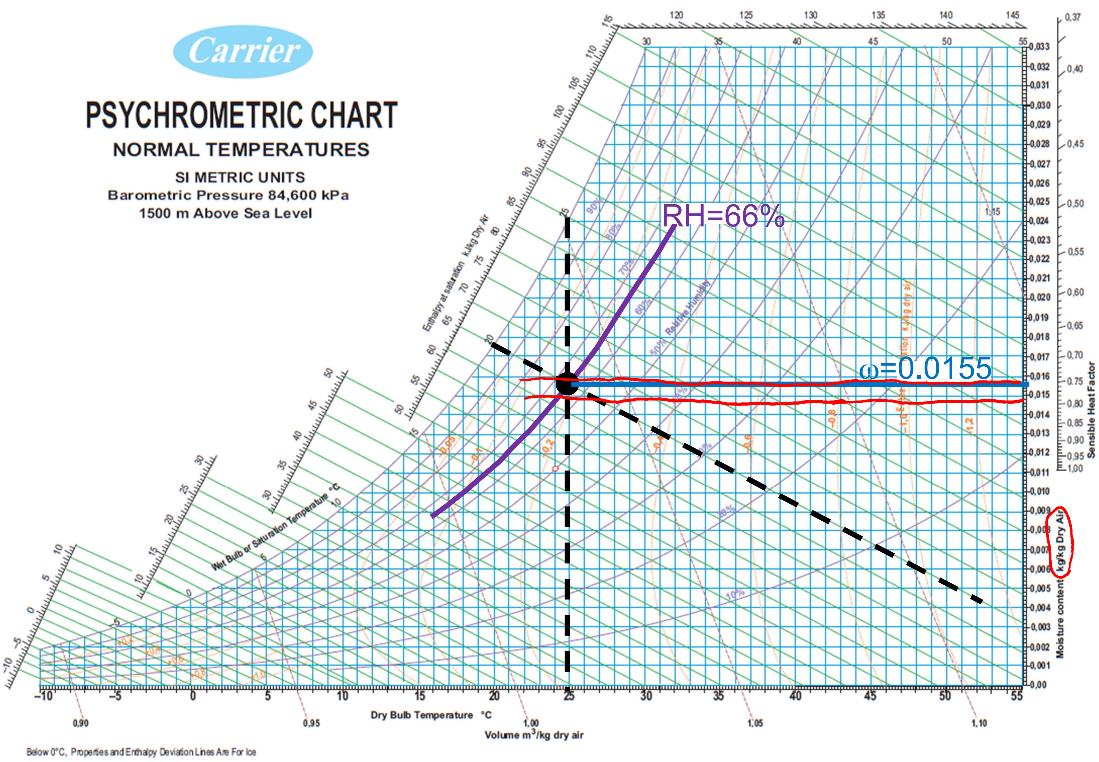
35

Given: $T_{db} = 25°\mathrm{C}$, $T_{wb} = 20°\mathrm{C}$ Find: RH, ω, v, h



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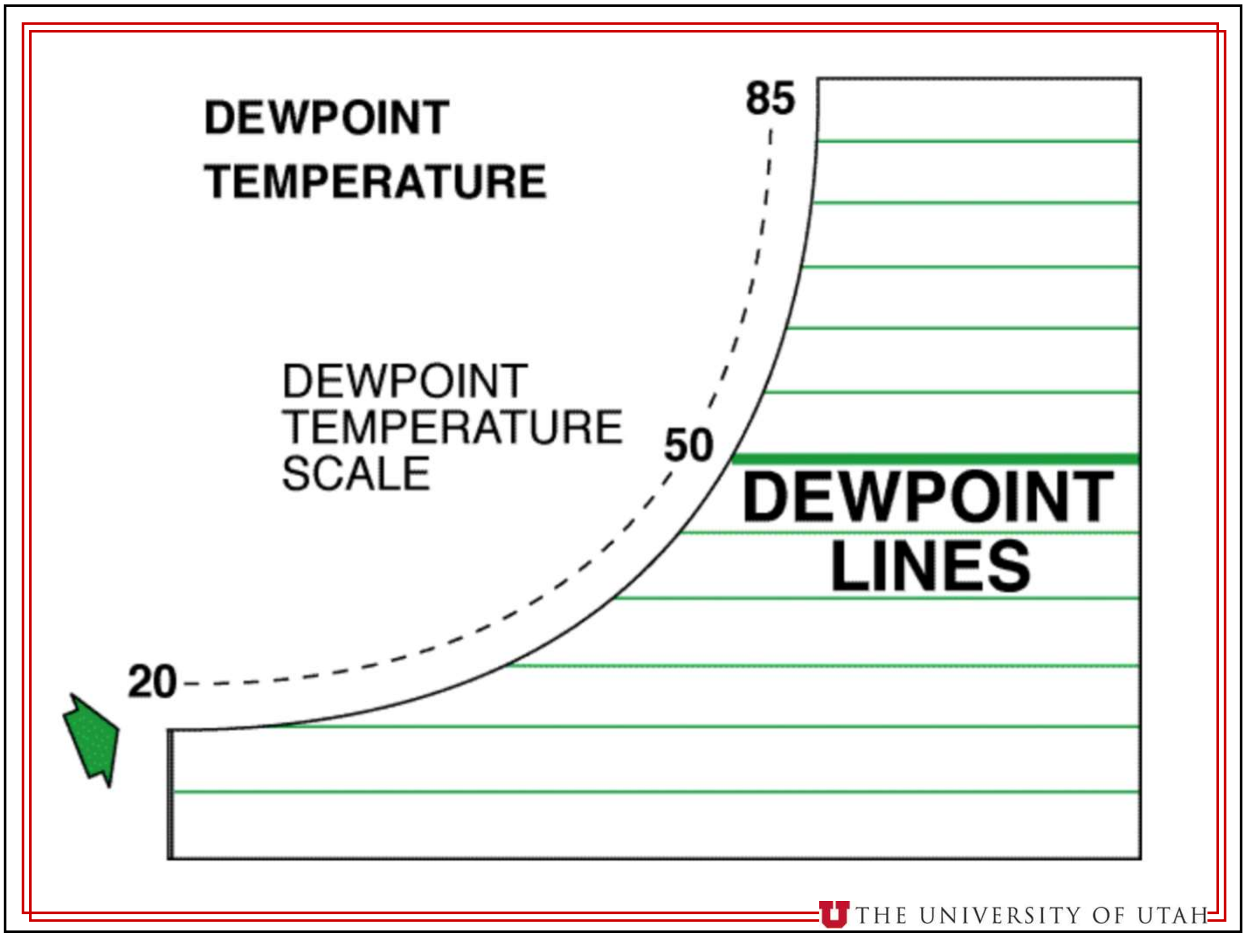
36


DEWPOINT
TEMPERATURE
85
DEWPOINT
TEMPERATURE
SCALE
50
DEWPOINT
LINES
20
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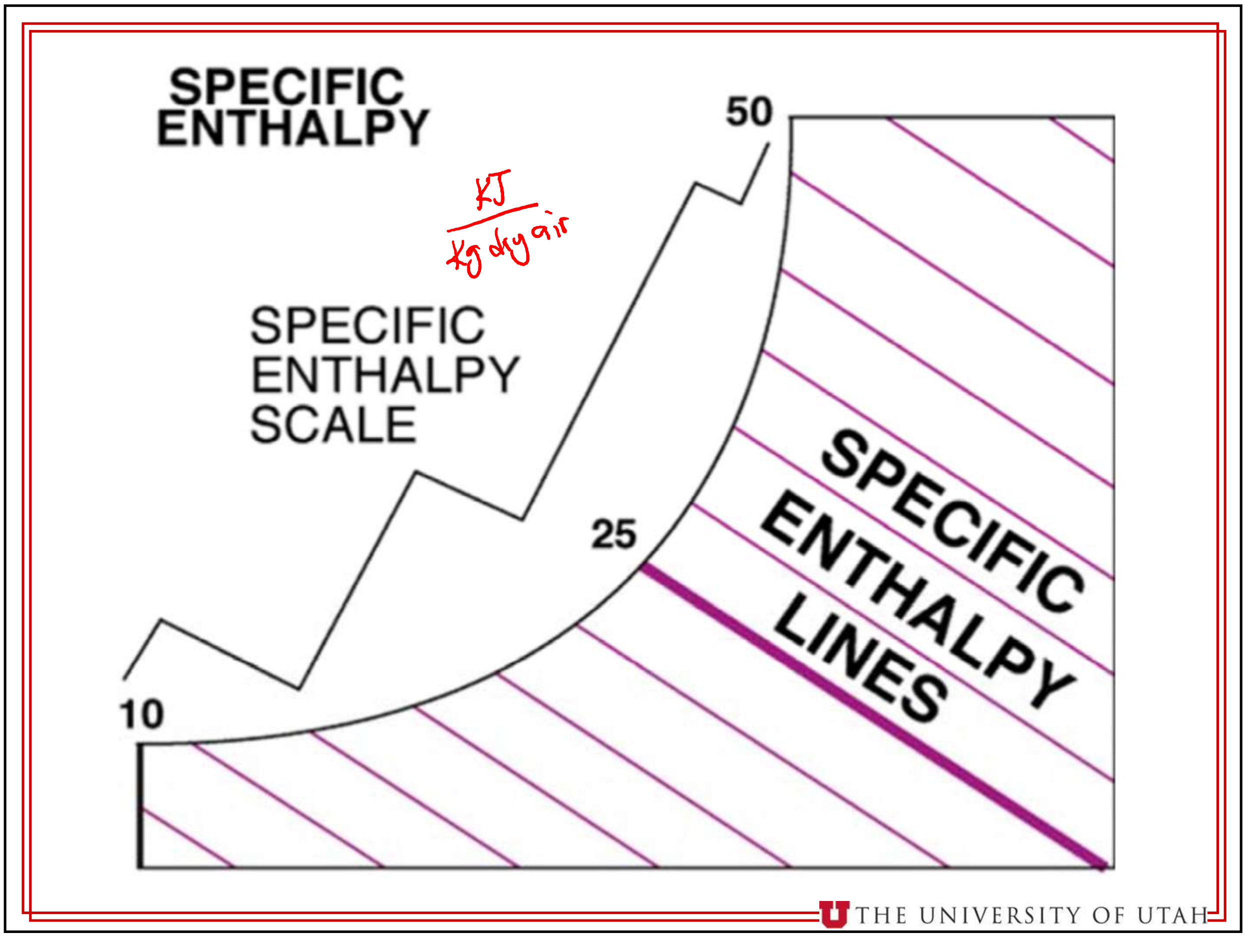
37


SPECIFIC
ENTHALPY
KJ / Kg dry air
50
SPECIFIC
ENTHALPY
SCALE
25
10
SPECIFIC
ENTHALPY
LINES
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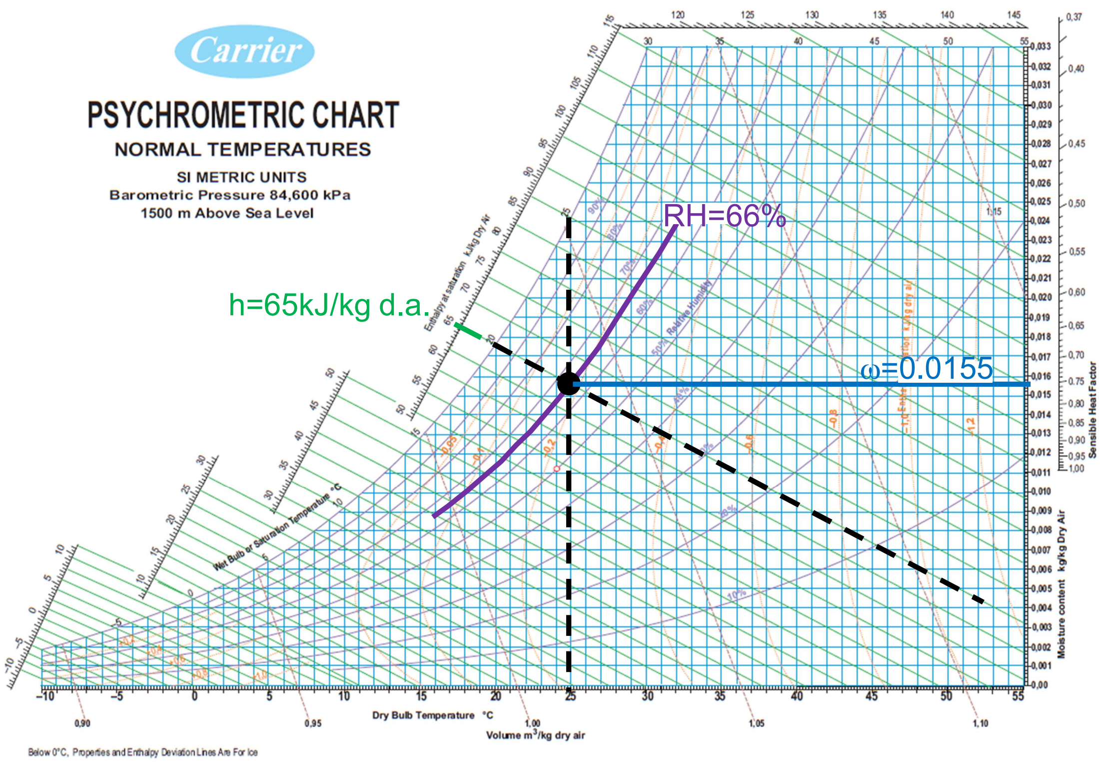
38

Given: $T_{db} = 25°C$, $T_{wb} = 20°C$ Find: RH, ω, v, h



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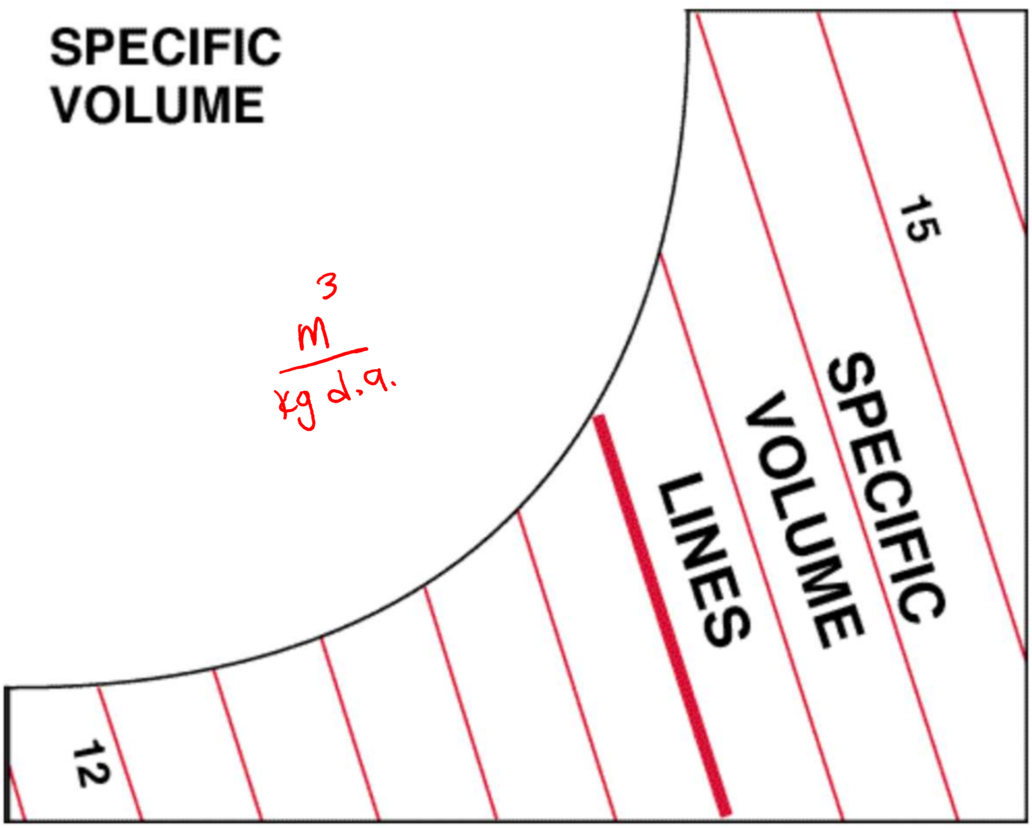
SPECIFIC VOLUME

$\frac{m^3}{kg\ d.a.}$



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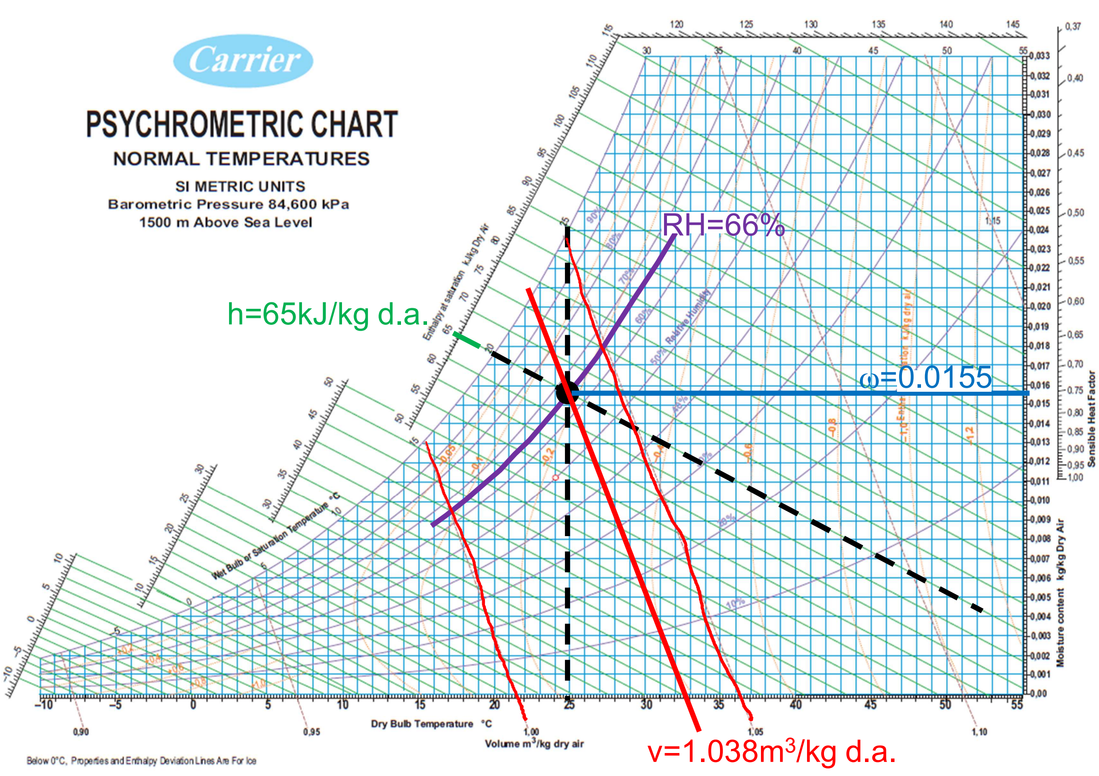
40

Given: $T_{db} = 25°\text{C}$, $T_{wb} = 20°\text{C}$ Find: RH, ω, v, h



41

Matlab Function: "Psychrometrics"

```
function [Tdb, w, phi, h, Tdp, v, Twb] = Psychrometrics (varargin)
% function [Tdb, w, phi, h, Tdp, v, Twb] = Psychrometrics (varargin)
%
% ACCEPTED VARIABLES
%   Tdb (dry bulb temperature) and Tdp(dew point temperature) in C
%   w (humidity ratio) in kg/kg of dry air
%   phi (relative humidity) in %
%   h (enthalpy) in J/kg of dry air
%   v (specific volume) in m3/kg of dry air
%   Twb (wet bulb temperature) in C
%   P (atmospheric pressure) in kPa
```

oC oC kPa

```
[Tdb,w,phi,h,Tdp,v,Twb]=Psychrometrics('tdb',25,'twb',20,'p',86);
```

dry bulb wet bulb atm. pressure

For - Loop

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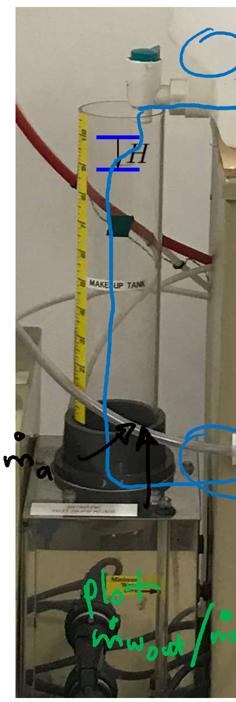
Conservation of Mass (Water)



$$\dot m_{w_{in}} + \dot m_{v_{in}} = \dot m_{v_{out}} + \dot m_{w_{out}}$$

$$\dot m_{w_{out}} = \underbrace{\dot m_{w_{in}}}_{\text{measured}} + \dot m_{v_{in}} - \dot m_{v_{out}}$$

$$\dot m_v = \omega \, \dot m_a$$

mass flow rate dry air (orifice meter)

specific humidity (psychrometric function)

$$\underset{[kg/s]}{\dot m_a} = C\sqrt{\rho \Delta P} = \boxed{0.0137}\sqrt{\frac{\Delta P}{(1+\omega)v_a}}$$

ΔP → measured

ω, v_a → psychrometric function

ΔP : mm H_2O

$$\underset{[kg/s]}{\dot m_{w_{out}}} = \underbrace{\dot m_{w_{in}}}_{\substack{\text{measured} \\ [kg/s]}} + \underbrace{\dot m_a}_{\substack{\text{measured} \\ [kg/s]}}\underbrace{(\omega_{in} - \omega_{out})}_{\substack{\text{psychrometric function} \\ \text{kg w.v./kg dry air}}}$$

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43

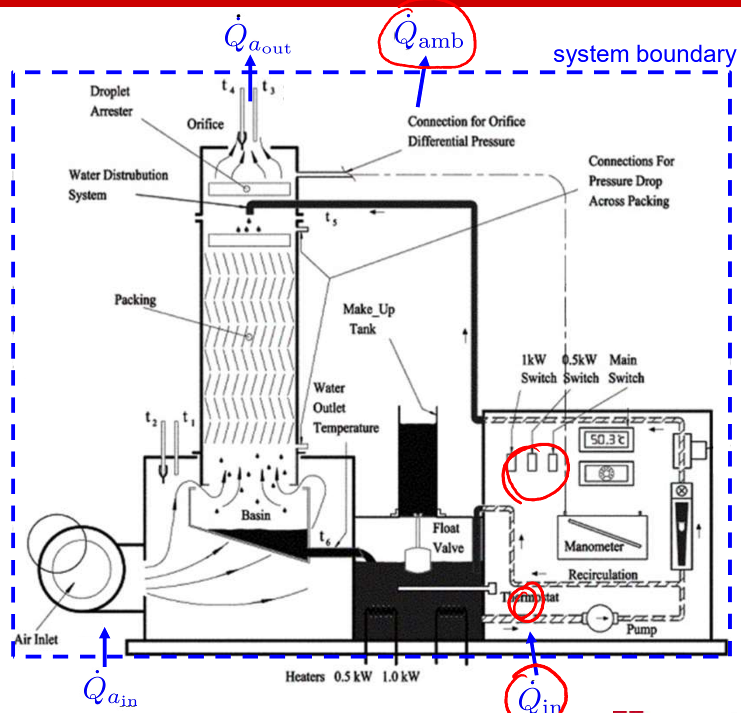
Conservation of Mass (Water)

$$\dot{m}_{makeup} = \dot{m}_{w_{in}} - \dot{m}_{w_{out}}$$
$$= \dot{m}_a (\omega_{out} - \omega_{in})$$

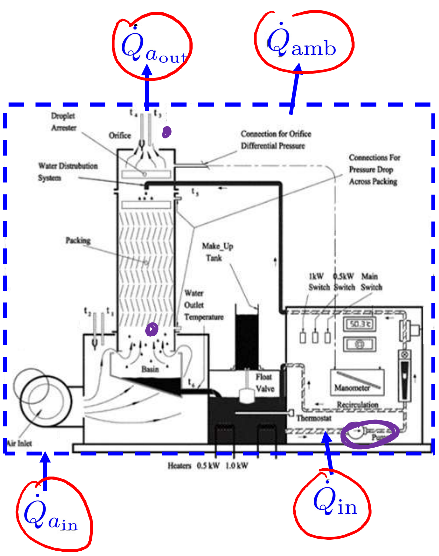
In lab,

$$\rightarrow \dot{m}_{makeup} \approx \frac{\pi/4 \, D^2 H \rho_w}{t}$$

Conservation of Energy (System)



Conservation of Energy (System)



Rate of heat gain by air, Q_a :

$$\dot{Q}_a = \dot{Q}_{a_{out}} - \dot{Q}_{a_{in}}$$

$$\rightarrow \dot{Q}_a = \underbrace{\dot{m}_a}_{\text{measured}} \underbrace{(h_{a_{out}} - h_{a_{in}})}_{\text{psychrometric function}}$$

Rate of heat lost to surroundings, Q_{amb} :

$$\dot{Q}_{a_{in}} + \dot{Q}_{in} = \dot{Q}_{a_{out}} + \dot{Q}_{amb}$$

$$\dot{Q}_{amb} = \underbrace{\dot{Q}_{in}}_{1.5\,kW + 0.1\,kW} + \underbrace{\dot{Q}_{a_{in}} - \dot{Q}_{a_{out}}}_{-\dot{Q}_a}$$

$$\dot{Q}_{amb} = 1.6\,kW - \dot{Q}_a$$

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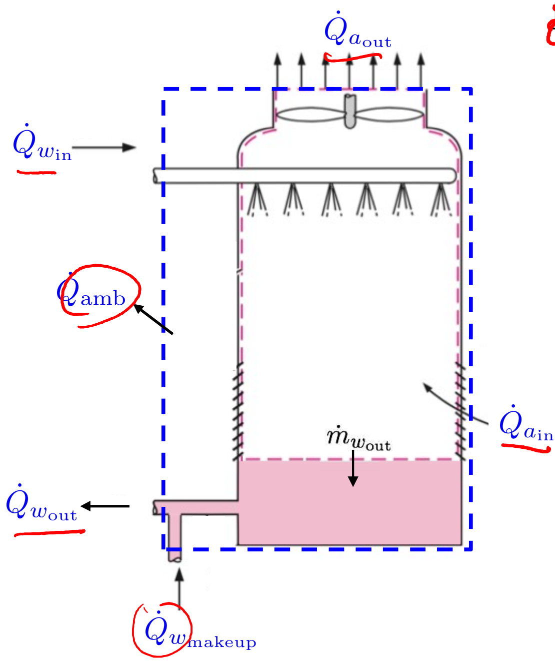
Conservation of Energy (System)



Rate of heat lost to surroundings $\dot{Q}_{amb}$:

$$\dot{Q}_{a_{in}} + \dot{Q}_{w_{in}} + \dot{Q}_{w_{makeup}} = \dot{Q}_{a_{out}} + \dot{Q}_{w_{out}} + \dot{Q}_{amb}$$

$$\dot{Q}_{amb} = \dot{m}_a \left(h_{a_{in}} - h_{a_{out}}\right) + \dot{m}_{w_{in}} h_{w_{in}} + \dot{m}_{makeup} h_{makeup} - \dot{m}_{w_{out}} h_{w_{out}}$$

sat. steam water

48

Questions??

Thank you for your attention!

Let me or the TAs know if you have questions

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48