CHE 318 Lecture 28

Humidification Process II

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Learning outcomes

After this lecture, you will be able to:

- **Recall** humidification and cooling paths on the psychrometric chart.
- **Describe** the origin of wet-bulb temperature and latent-heat effects during evaporation.
- **Analyze** adiabatic saturation using coupled heat and mass balances.
- **Apply** the psychrometric chart to obtain humidity-related properties.

Cheatsheet for humidification process

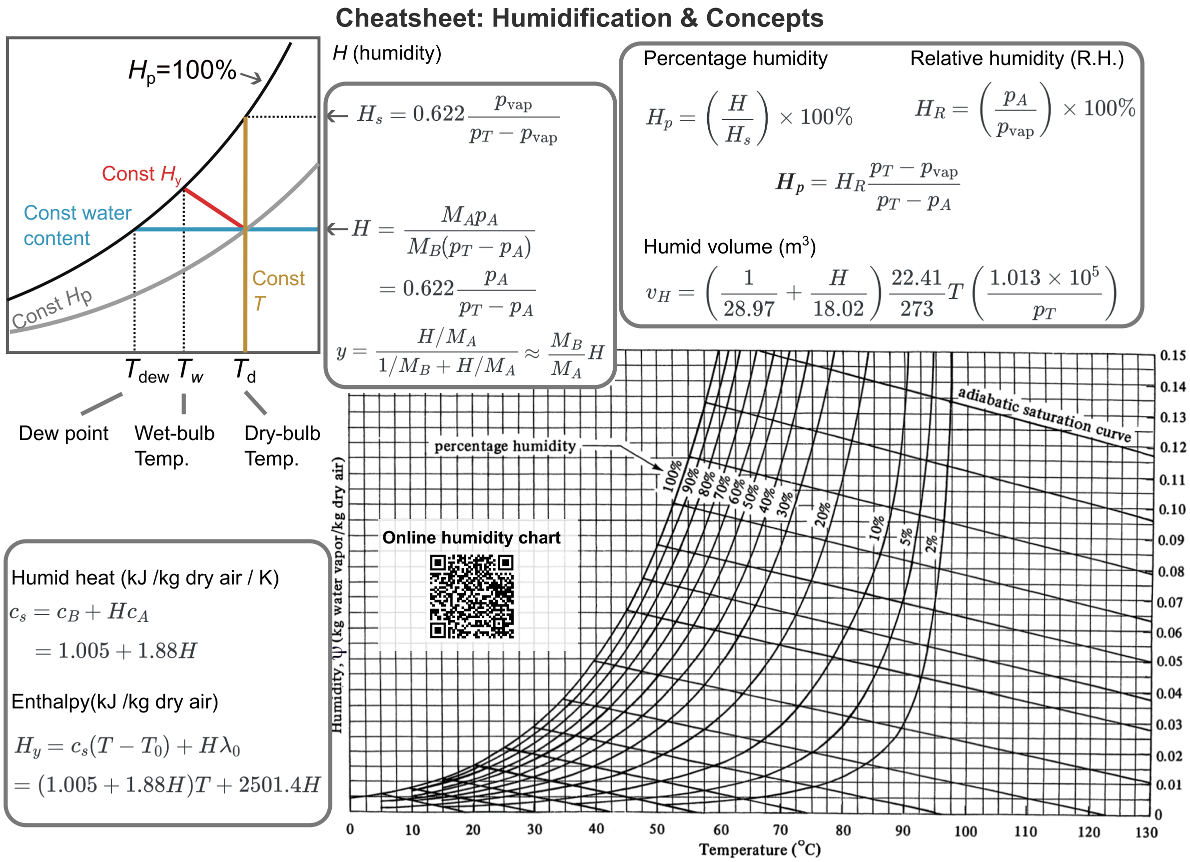


Figure 1: Charts distributed in class.

Reading the humidity / psychrometric chart (level 1)

Find where H, H_p, dew point T_{dew} are?

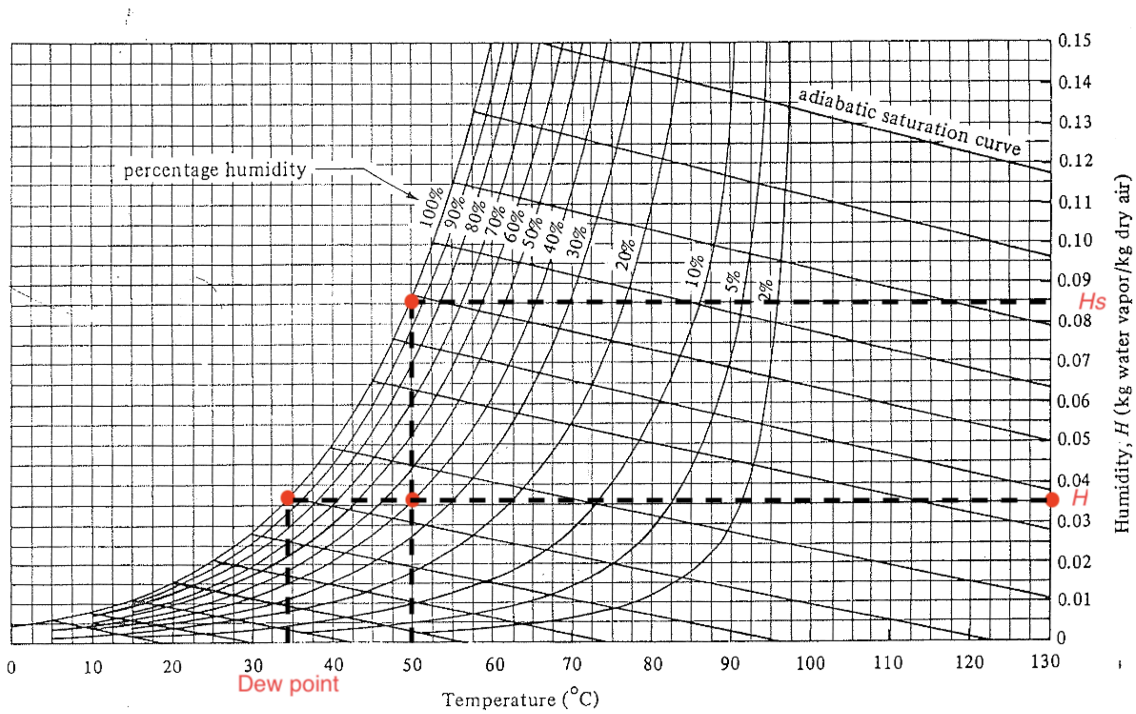


FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

Example 2: humidifier design

A living room of 60 m^2 at 22 °C has a relative humidity of 20% due to continuous heating. You and your roommate wish to purchase a humidifier that can humidify the living room up to 45% relative humidity. Assume the floor-ceiling distance is 3 m, calculate the weight of water needed to humidify the whole room. Can you use the humidity chart to estimate?

Example 2: steps

1. Read the saturation vapour pressure from H_s ($H_s = 0.017$)

$$H_s = 0.622 \frac{p_{\text{vap}}}{p_T - p_{\text{vap}}} = 0.017 \quad (1)$$

$$p_{\text{vap}} = 2.69 \text{ kPa} \quad (2)$$

from the vapour data it gets $p_{\text{vap}} = 2.64$ kPa, pretty close!

2. Estimate weight of water Δm_A

$$
\begin{aligned}
\Delta m_A &= \frac{\Delta p_A V M_A}{RT} && (3)\\
&= \frac{(H_{R1} - H_{R0}) p_{\text{vap}} V M_A}{RT} && (4)\\
&\approx 0.87 \text{ kg} && (5)
\end{aligned}
$$

Does it make sense? The requirement for water tank will be a lower bound.

Mythbusting time (1)

My weather app shows that outside is −12 °C and R.H. is 74%, where the dew point is −16 °C. What does all that mean?

> Tip
>
> A useful note is that the **lower** dew point is compared with current temperature, the **drier** air appears to be

Mythbusting time (2)

In the previous scenario −12 °C and R.H. is 74%, when I open the door, my humidity in home immediately drops! Why?

- The calculated H_R at room temperature is only 6.7% if fully filled with outside air.

> Tip
>
> H_R (or R.H.) only measures up at current temperature. When moving water content at different T, H_R will change.
>
> - cold air appears to be dry at high T
> - warm air appears to be humid at low T

Mythbusting time (3)

Why does "humid hot" environment feels much hotter than "dry hot" environment, even if the apparent T is the same?

- Calculate the enthalpy of air-water mixture, H_y significantly increases when relative humidity is high!
- Human body relies on cooling to survive. At high T high H_R, both driving forces for evaporation are reduced:
  - $T_{\text{body}} - T_{\text{env}}$ becomes small   bad dissipation
  - $p_{A,\text{body}} - p_{A,\text{env}}$ becomes small   evaporation suppressed

> Tip
>
> The sensible specific heat for air-water mixture does not change significantly, even if water vapour's heat capacity is higher. (absolute H is always 0.1 when $T < 50\ ^\circ\text{C}$)

Measuring humidity: the two-bulb hygrometer

Before electronic sensors, humidity was measured using a **two-thermometer setup**

- One thermometer measures **dry-bulb temperature** T_d
- The second thermometer is wrapped with a **wet wick** and measures **wet-bulb temperature** T_w ($T_w < T_d$)

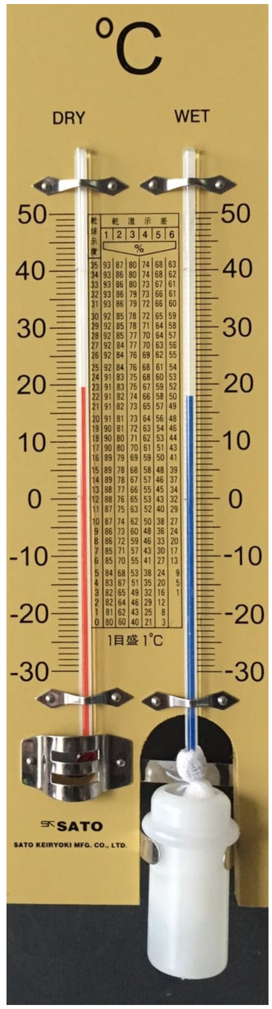


Figure 2: Two-bulb hygrometer

What does the wet bulb tell us?

The wet bulb is a **steady state** evaporative cooling experiment, which can be generalized for interfacial evaporation problem:

- In and outlet temperatures are the same, while outlet humidity is higher
- Evaporation consumes **latent heat**

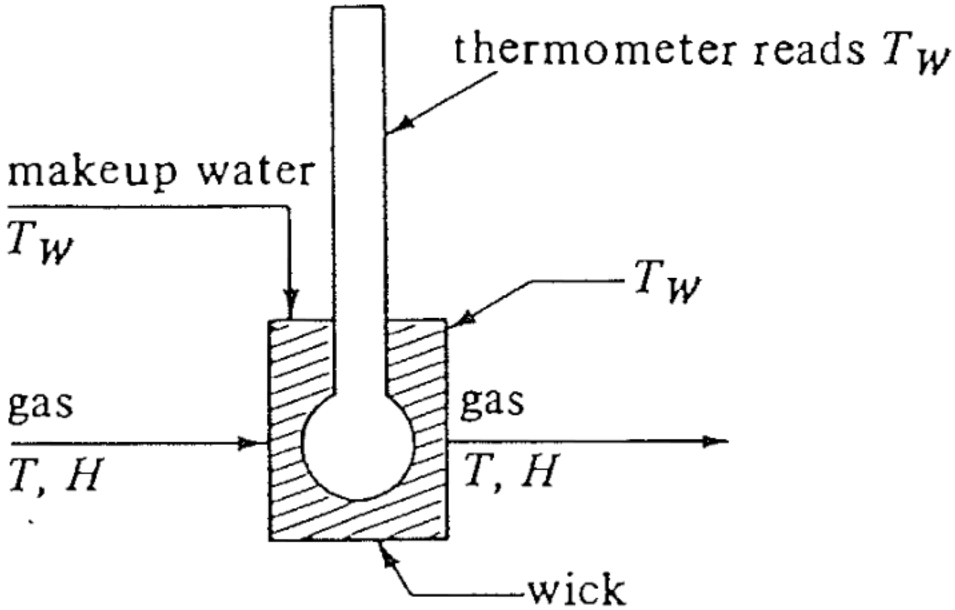


FIGURE 9.3-4. *Measurement of wet bulb temperature.*

Concept of wet-bulb temperature

- The wet-bulb temperature T_w is the temperature reached by a **wet surface exposed to air**

$$T_w < T_d$$

- T_d = dry-bulb temperature
- T_w = wet-bulb temperature
- The difference between T_w and T_d indicates the inlet air humidity

Moist air enthalpy

From Lecture 27, the specific enthalpy of moist air can be written as

$$H_y = (1.005 + 1.88H)(T - T_0) + 2501.4H \tag{6}$$

- Increase the absolute humidity H must cause H_y to increase gas phase takes heat from liquid.
- Solving the heat + mass balance will give solution to T_w.

Heat balance around the wet bulb

Consider the control volume around the wet bulb. Heat transferred from the air is used to evaporate water, linked by the heat-mass balance (need a bit prerequisite in heat transfer):

$$q = M_A \lambda_w A N_A \tag{7}$$

- m_A: molecular weight of water
- λ_w: latent heat of vaporization at T_w (44045 kJ/kg mol at 1 atm)
- A: area of the wetted surface
- N_A: molar flux of evaporating water

R.H.S.: mass transfer at the interface

The evaporation rate can be written as

$$N_A = k_y(y_w - y) \tag{8}$$

- k_y: gas-phase mass transfer coefficient (since $y_{BM} \approx 1$, $k_y \approx k'_y$)
- y_w: vapor mole fraction at the interface (saturated at T_w)
- y: vapor mole fraction in bulk air

Converting humidity to mole fraction

We can further change y to the humidity H for dilute system. Since humidity is define as weight ratio:

$$H = \frac{\text{kg } H_2O}{\text{kg dry air}} \tag{9}$$

The mole fraction of vapor is

$$y = \frac{H/M_A}{1/M_B + H/M_A} \tag{10}$$

Since humidity is typically small

$$y \approx \frac{M_B}{M_A} H \tag{11}$$

L.H.S. heat transfer to the wet surface

The heat flux q in L.H.S. from the air to the wet surface is

$$q = h(T - T_w)A \tag{12}$$

where h is heat transfer coefficient in the Fourier's law $q = -h\Delta T$

Wet-bulb setup: final results

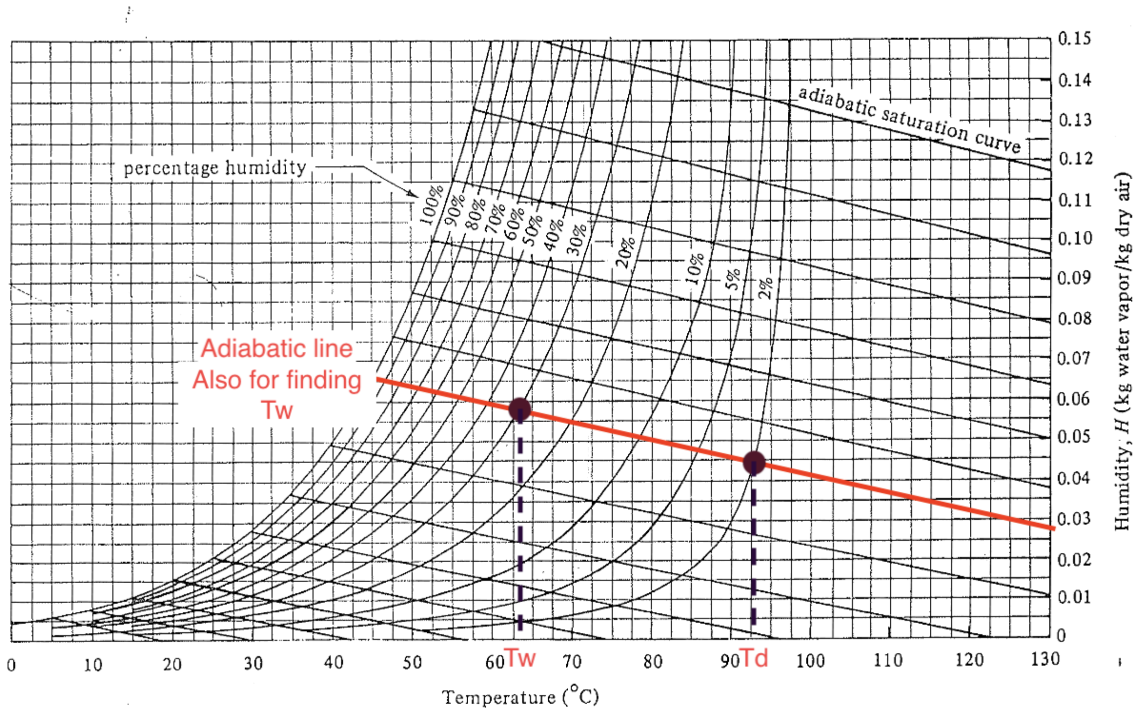
Combining heat transfer (q) and mass transfer (N_A) relations gives

$$\frac{H - H_w}{T - T_w} = -\frac{h}{M_B k_y \lambda_w} \tag{13}$$

Note $\frac{H-H_w}{T-T_w}$ means the slope of a line on the psychrometric chart. The slope is almost identical to **adiabatic line**!

Psychrometric chart: adiabatic line (level 2)

The (T_d, H_{in}) and (T_w, H_{out}) points are along the adiabatic line (no external heat exchange). For water-air system, the adiabatic line and cooling line are very close and often not distinguished.



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Deeper look into the cooling process (1)

What does the adiabatic line tell us? It is basically a process that each point has the same humid enthalpy, and no change of heat to external system:

$$H = c_s(T - T_0) + H\lambda_0 = [\text{Const}]$$

- Increase humidity   decrease T
- Lowest temperature can reach in the system at certain H_{out} is T_w
- Lowest temperature can reach when air is saturated is T_s

Deeper look into the cooling process (2)

For water-air, one handy property is that

$$\frac{h}{M_B k_y} \approx 1.005 \approx c_s \qquad \text{[kJ / kg air]}$$

such relation allows us to use the humidity chart's adiabatic saturation curve.

> ⚠ Warning
>
> Such simplification may not be applicable for other liquid, such as benzene!

What to learn next

The wet-bulb experiment connects **heat transfer** and **mass transfer**, and the evaporation rate depends on the **vapor pressure driving force**.

Next topics we will study:

- Gas-phase mass transfer during evaporation
- Interfacial equilibrium between water and air
- Driving force expressed as $(y_w - y)$ or $(p_{sat} - p_A)$

Summary

- Reading humidity chart for cooling process
- Wet-bulb temperature and its origin
- Calculation of humidity values from the chart + equation