CHE 318 Lecture 27

Introduction of Humidification Process

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Learning outcomes

After this lecture, you will be able to:

- **Recall** common measures used to express water content in air.
- **Describe** how humidity changes with temperature and saturation conditions.
- **Apply** equations for humid-air properties such as humid heat and enthalpy.
- **Explain** why humidification couples mass transfer with heat effects.

Humidification process: why is it relevant?

Edmonton's winter is harsh! How do we make our home more humid?

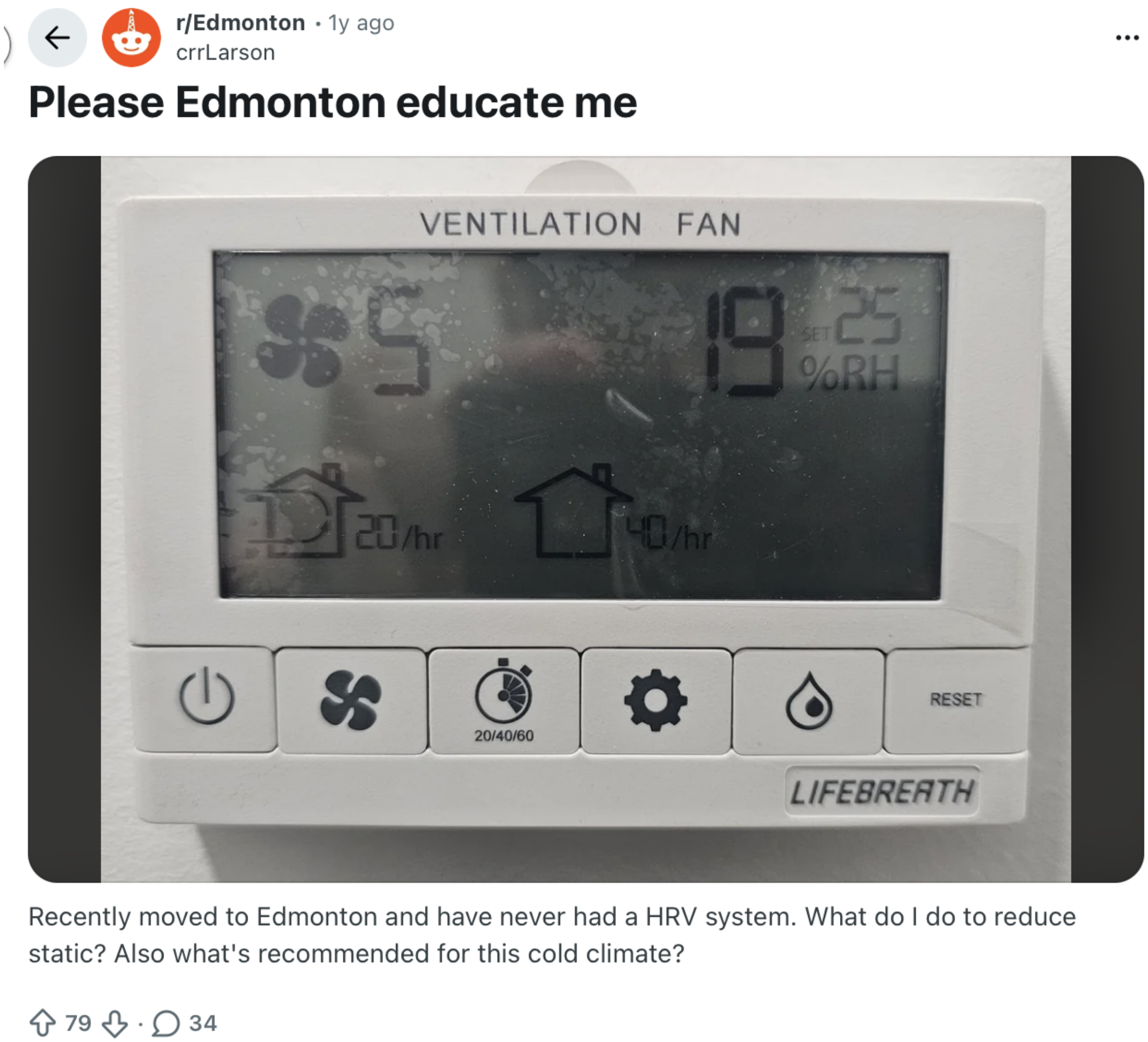


Figure 1: A random reddit post

The humidification process: two-phase mass & heat transfer

In order to increase the humidity in a room during Edmonton's harsh winter, you decide to buy a humidifier. Your knowledge from the CHE 318 course may actually be helpful! A few questions to think about:

- What is humidity, anyway?
- Types of humidifiers available?
- How does each of them work?

- Is it efficient for my use scenario?

Humidifiers: how do they work?

- What is the common feature? Increase water content in air
- Can you use mass transfer concepts to explain their mechanism?

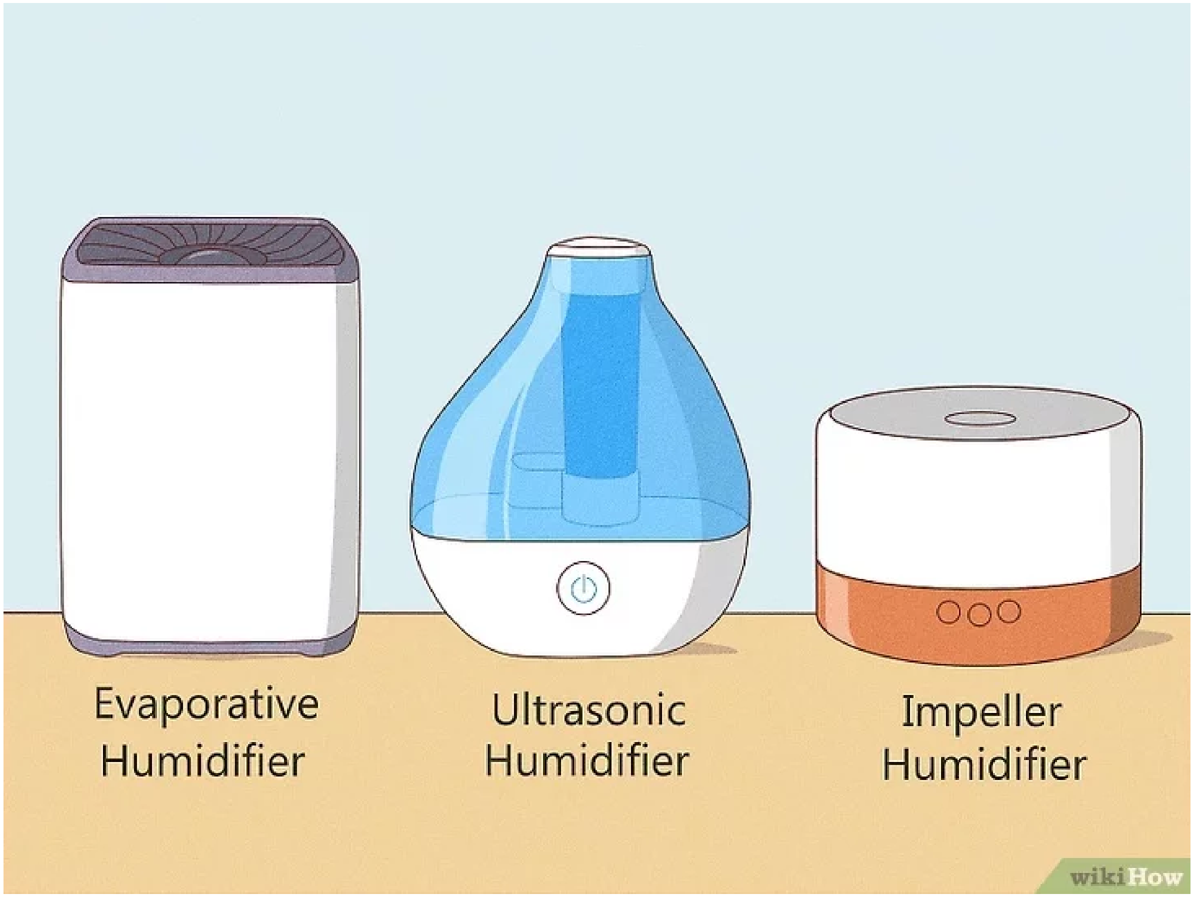


Figure 2: Wikihow comparison on humidifiers

Concept 1: humidity

Humidity H (an absolute value)

- Definition: kg of water vapor per kg dry air at certain temperature

- For water-air systems where molecular weights are M_A and M_B, respectively, this also links to partial pressure p_A

$$H = \frac{M_A p_A}{M_B(p_T - p_A)}$$

- For air-water, can simply as

$$H = 0.622 \frac{p_A}{p_T - p_A}$$

Concept 2: saturation vapour pressure and saturation humidity

At each temperature T, at equilibrium water-air interface, the pressure is **saturation vapour pressure** p_{vap}. The (absolute) humidity at this partial pressure is the **saturation humidity** H_s:

$$H_s = 0.622 \frac{p_{\text{vap}}}{p_T - p_{\text{vap}}}$$

Concept 3: percent humidity and relative humidity

These two are often confused with each other so treat with caution.

- **Percent humidity**, percentage of current humidity H with respect to saturation humidity H_s
  - Often appear in ChemE textbooks and charts: easy to calculate with H

$$H_p = \left(\frac{H}{H_s}\right) \times 100\%$$

- **Relative humidity**: percentage of current partial pressure p_A with respect to (saturation) vapour pressure p_{vap}
  - The actual one used in household humidity sensor (also called R.H.)

$$H_R = \left(\frac{p_A}{p_{\text{vap}}}\right) \times 100\%$$

H_p and H_R are generally not the same. The approximation $H_p \approx H_R$ only applies at low humidity.

Relationship between H_p and H_R

Using the ideal gas law, it can be shown that

$$H_p = \frac{p_A}{p_{\text{vap}}} \frac{p_T - p_{\text{vap}}}{p_T - p_A} \quad (1)$$

$$= H_R \frac{p_T - p_{\text{vap}}}{p_T - p_A} \quad (2)$$

Since $p_A \leq p_{\text{vap}}$, we can show that $H_p \leq H_R$ always holds.

Example of percentage / relative humidity calculation

EXAMPLE 9.3-1. Humidity from Vapor-Pressure Data
The air in a room is at 26.7°C (80°F) and a pressure of 101.325 kPa and contains water vapor with a partial pressure $p_A = 2.76$ kPa. Calculate the following:

(a) Humidity, H.
(b) Saturation humidity, H_S, and percentage humidity, H_P.
(c) Percentage relative humidity, H_R.

Solution: From the steam tables at 26.7°C, the vapor pressure of water is $p_{AS} = 3.50$ kPa (0.507 psia). Also, $p_A = 2.76$ kPa and $P = 101.3$ kPa (14.7 psia). For part (a), using Eq. (9.3-1),

$$H = \frac{18.02}{28.97} \frac{p_A}{P - p_A} = \frac{18.02(2.76)}{28.97(101.3 - 2.76)} = 0.01742 \text{ kg } H_2O/\text{kg air}$$

For part (b), using Eq. (9.3-2), the saturation humidity is

$$H_S = \frac{18.02}{28.97} \frac{p_{AS}}{P - p_{AS}} = \frac{18.02(3.50)}{28.97(101.3 - 3.50)} = 0.02226 \text{ kg } H_2O/\text{kg air}$$

The percentage humidity, from Eq. (9.3-3), is

$$H_P = 100 \frac{H}{H_S} = \frac{100(0.01742)}{0.02226} = 78.3\%$$

For part (c), from Eq. (9.3-4), the percentage relative humidity is

$$H_R = 100 \frac{p_A}{p_{AS}} = \frac{100(2.76)}{3.50} = 78.9\%$$

Concept 4: dew point

Dew point: temperature at which the vapor in air just becomes saturated / condensed.

At dew point, $p_A = p_{\text{vap}}(T_{\text{dew}})$

- Lower dew point means drier air (compared with current temperature p_{vap}

Concept 5: humid heat

Humid heat c_s: heat required to raise 1 kg *dry air* plus its associated vapor by 1 K. Think of it as the specific heat / heat capacity for air-water mixture.

For air-water, when dry air and water vapour have heat capacities c_B and c_A, respectively, the humid heat is

$$c_s = c_B + Hc_A$$

Useful relation to remember:

$$c_s = 1.005 + 1.88H \quad [\text{kJ/(kg dry air K)}]$$

Heat required for a humid gas stream

The relation for c_s tells us that heating up a gas stream for humid air requires more energy than drier one. For a stream containing dry air and water vapor, such heat is:

$$Q = w_B c_s \Delta T$$

where w_B is mass flow rate of dry air in kg / s. Note such energy is usually called **sensible** heating of the gas-vapor mixture, because it is directly proportional to ΔT.

Concept 6: humid volume

Humid volume v_H: volume occupied by 1 kg dry air plus its associated water vapor at certain pressure. (This is less useful than other quantities for cooling process).

At 1 atm:

$$v_H = \frac{22.41}{273}\left(\frac{1}{28.97} + \frac{H}{18.02}\right) T$$

At general pressure:

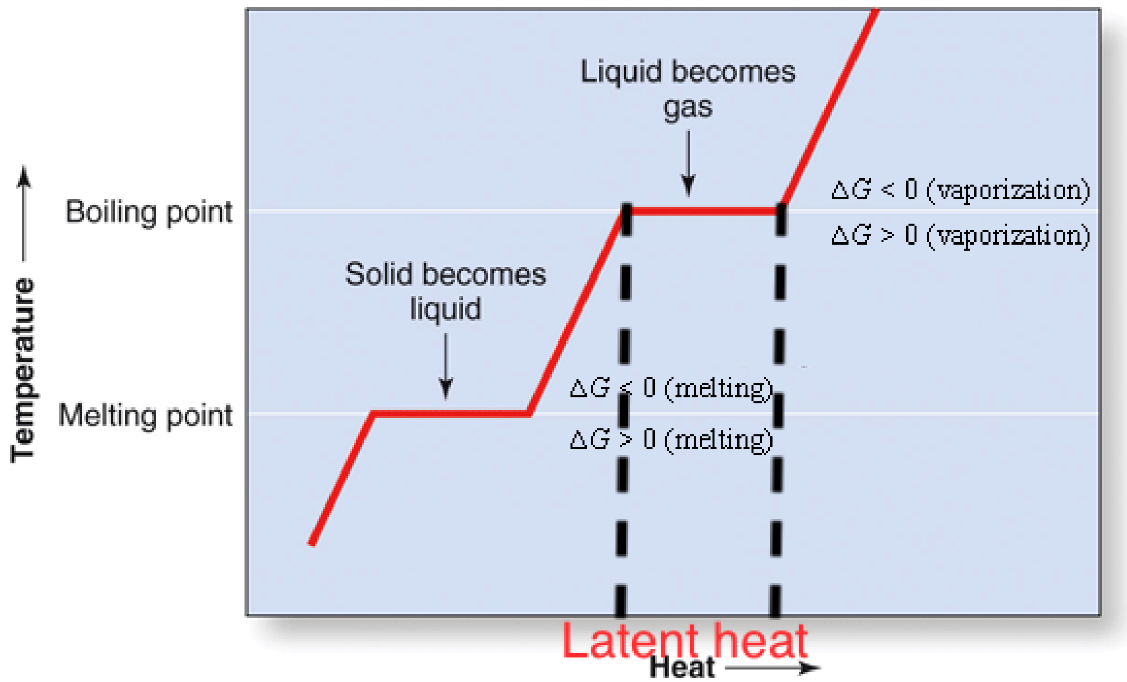
$$v_H = \left(\frac{1}{28.97} + \frac{H}{18.02}\right)\frac{22.41}{273} T \left(\frac{1.013 \times 10^5}{p_T}\right)$$

where T is in Kelvin, p_T is in Pa, and v_H is in m^3.

Concept 7: enthalpy of humid air

Humid air **enthalpy** H_y includes:

- **sensible heat** of dry air and vapor: proportional to ΔT
- **latent heat** carried by water vapor: caused by phase-change, T remains the same



Enthalpy of humid air: general form:

- Usually written as H_y (not to be confused with other forms of humidity H, H_p and H_R).
- Unit: kJ / kg dry air
- Enthalpy is a *relative* quantity, so a reference temperature T_0 should be used (usually $T = 0\ ^\circ\mathrm{C}$)

$$H_y = c_s(T - T_0) + H\lambda_0$$

For air-water with $T_0 = 0^\circ\mathrm{C}$, and T uses Celcius:

$$H_y = (1.005 + 1.88H)T + 2501.4H \quad [\mathrm{kJ/kg\ dry\ air}]$$

Everything at one place: the humidity / psychrometric chart

Psychrometric: greek for *psychro* (cold) + *metric* (measure), relating to the measurement of temperature drop when water evaporates.

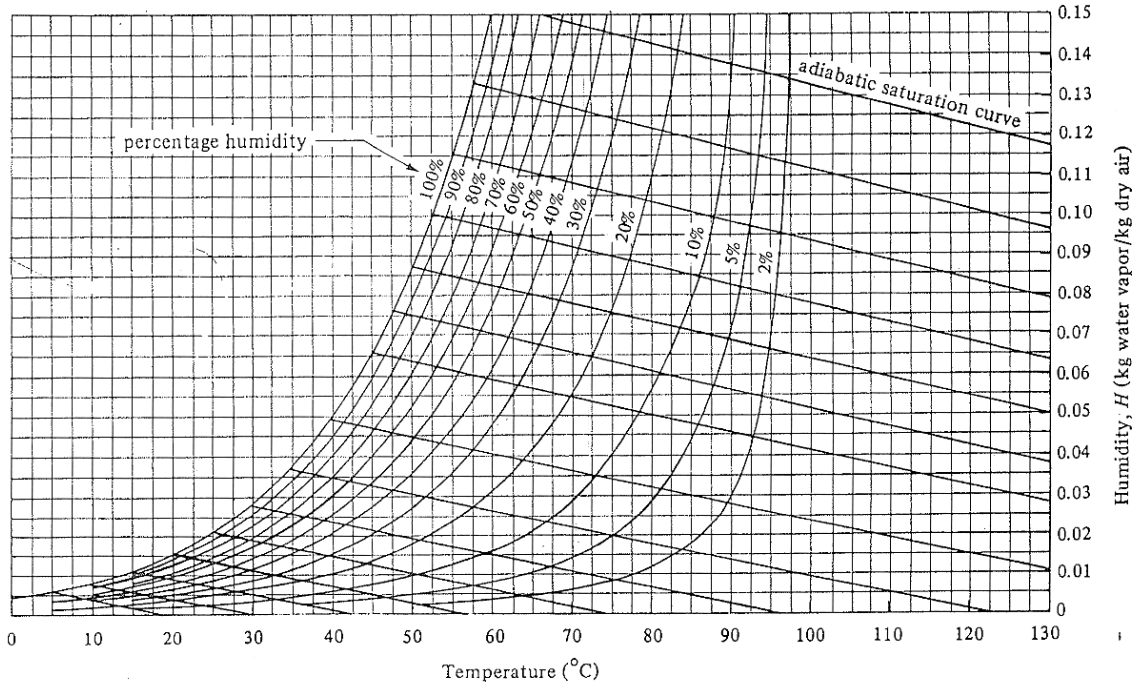
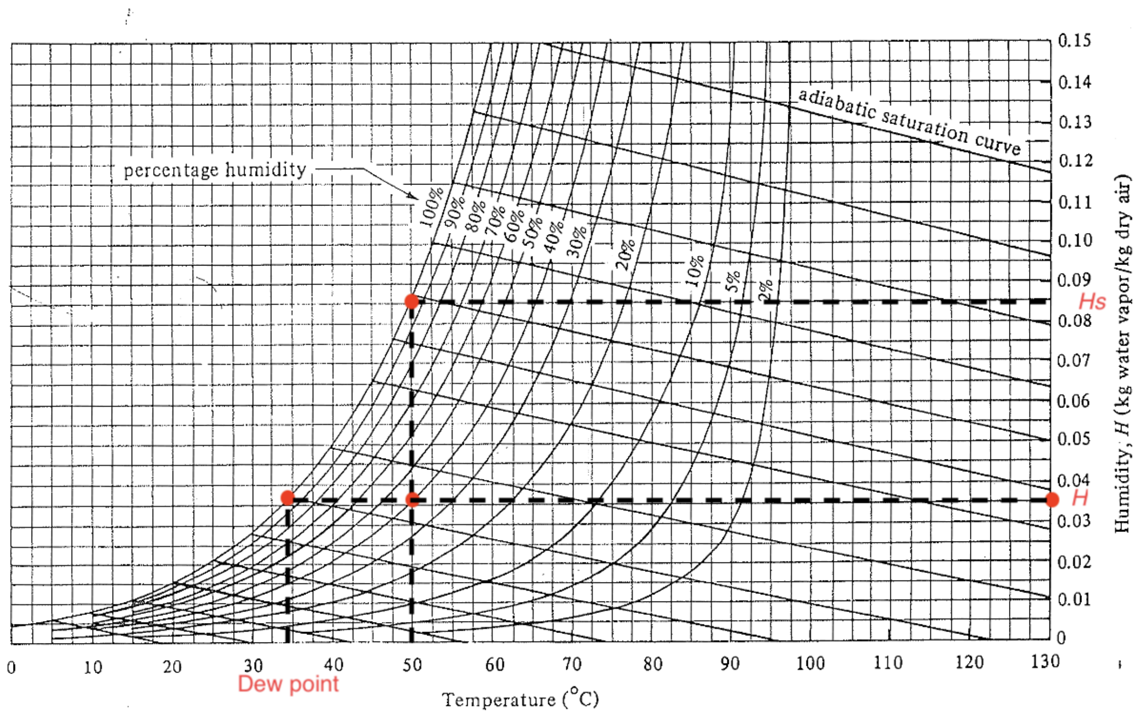


FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

Reading the humidity / psychrometric chart (level 1)

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



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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 ($H_s = 0.017$)

$$H_s = 0.622 \frac{p_{\text{vap}}}{p_T - p_{\text{vap}}} = 0.017 \tag{3}$$

$$p_{\text{vap}} = 2.69 \text{ kPa} \tag{4}$$

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

2. Estimate weight of water Δm_A

$$\begin{aligned}
\Delta m_A &= \frac{\Delta p_A V M_A}{RT} && (5)\\
&= \frac{(H_{R1} - H_{R0}) p_{\text{vap}} V M_A}{RT} && (6)\\
&\approx 0.87 \text{ kg} && (7)
\end{aligned}$$

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 $T < 50$ °C)

What to learn next

In industrial applications, evaporation of water into vapour is used to cool hot liquid. We will discuss in detail how to solve this using the concept of enthalpy in next lecture.

Summary

- Demystifying the humidification process: it's just mass transfer + heat transfer
- General concepts in humidification
- Different forms of humidity
- Humidity-dependent enthalpy and use of humidity chart