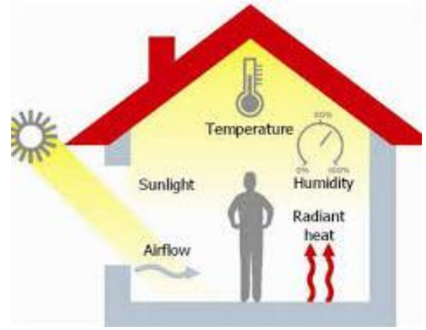
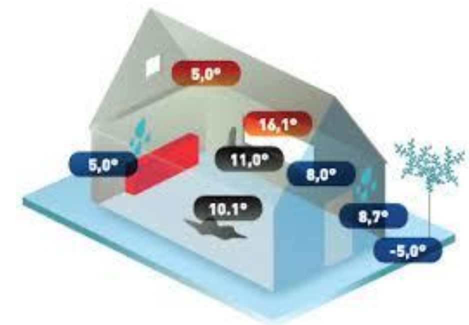
CIVIL 212
Indoor Climate
Fall 2024





Thermodynamic processes in HVAC

10 October, 2024

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Last time we covered…

We can assess thermal comfort in two ways:

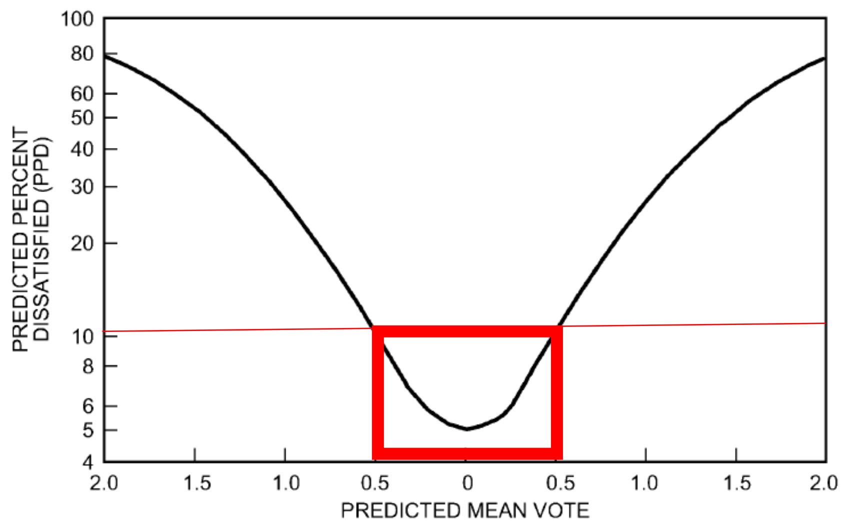
- Actual thermal comfort (through Actual Mean Vote)
- Predicted thermal comfort (through Predicted Mean Vote)

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

$-0.5 < PMV < +0.5$

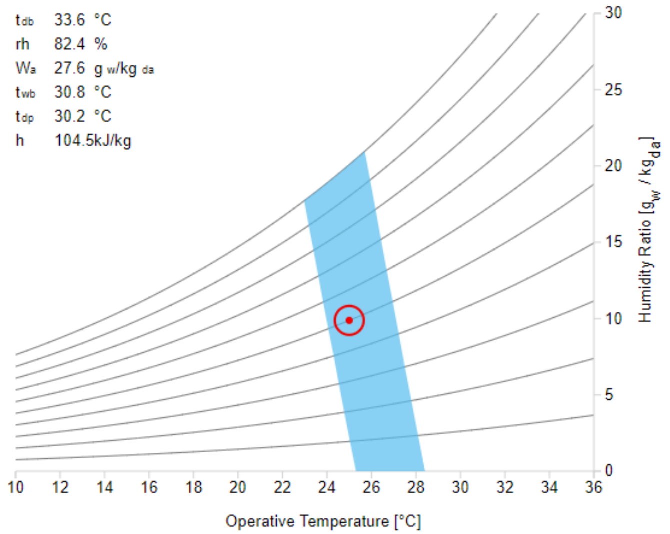
⇩

$PPD < 10\ \%$

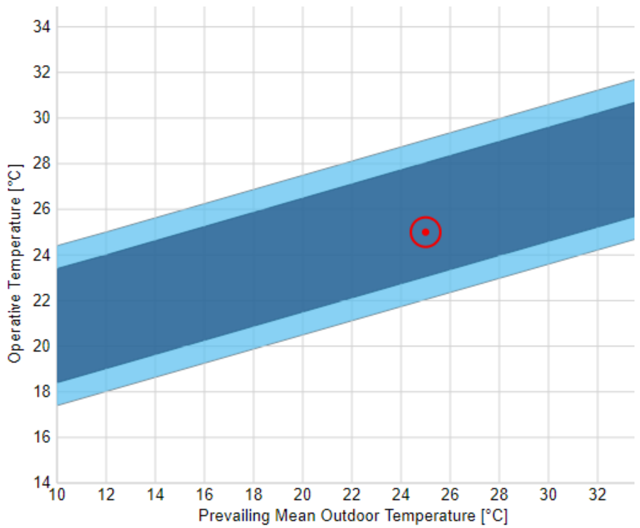


To predict thermal comfort, we can use:

- PMV/PPD (Static) model:
  - steady-state
  - 4 environmental factors
  - 2 personal factors



- Adaptive model:
  - Behavioral adaptation
  - Physiological adaptation
  - Psychological adaptation



Homework, exercise #5

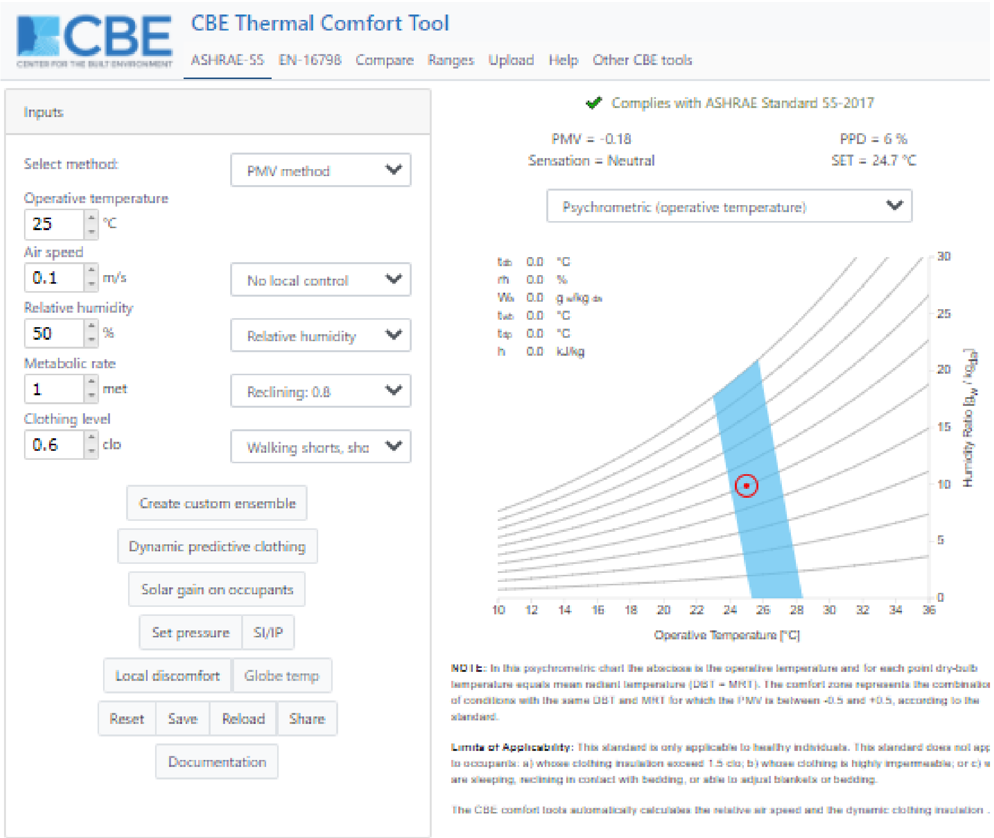
During the average summer month, indoor operative temperature is 24.5 °C, while outdoor temperature is 27.5 °C.

Q.1. According to ASHRAE, what is the needed range of operative temperature in order to preserve 90% acceptability limits?

***Solution**: 90% acceptability limits = Operative temperature: 23.8 to 28.8 °C*

Q.2. According to ASHRAE, which category of compliance is met?

***Solution**: ASHRAE has no categories (in EN-16798 it would be the second category)*



http://comfort.cbe.berkeley.edu/

Update on the midterm exam – What to study?

- If you understand the lecture notes, you will do well.
- The exam questions will be a combination of:
  - A few quiz questions with multiple choice answers based on theory. This will count for less points compared to other questions.
  - Calculations (be sure that you fully understand all the calculation examples from the classes, including general psychrometrics and psychrometrics of HVAC processes, unit conversion, CBE thermal comfort tool for prediction of thermal comfort, sensible and latent heat gains and losses through intentional and unintentional ventilation).
  - Open-ended questions (those you cannot answer with a simple “yes” or “no”, and instead require to critically think and to elaborate on your point). These question won’t necessarily have a single correct answer but will rather examine your perspective described in your own words.

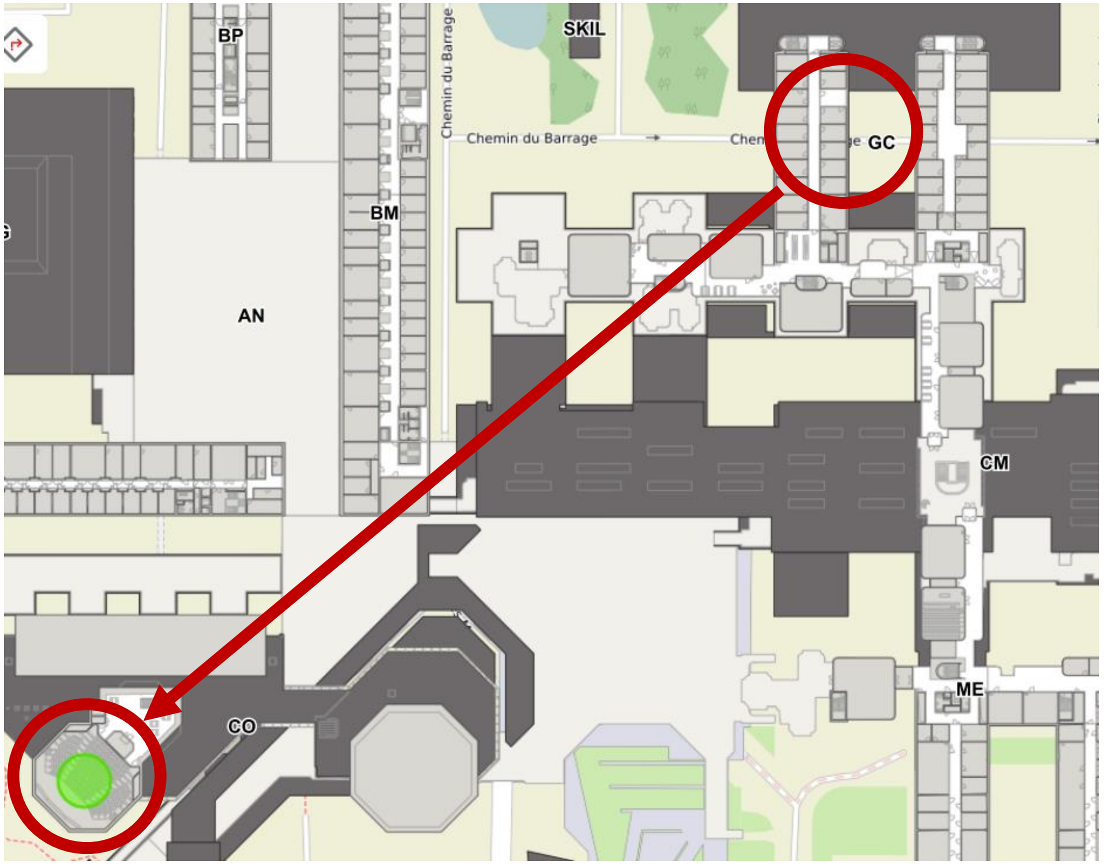
Update on the midterm exam – Info & Tips

- This will be an open book exam. You are free to use the lecture materials, but you must work on your own.
- Make sure that your calculators and psychometric charts are ready. You will also need a laptop to use CBE thermal comfort tool (make sure it's charged). The use of internet beyond the CBE tool is not allowed.
- Please be sure to show as much work as possible. I may give partial credit for it (in case your end result is incorrect).
- Some of open-ended questions won't have necessarily a single correct answer. For some of these questions how you set up the problem is just as important as whether or not you ultimately get the right answer.
- Please use English language only.
- If you have any questions about the wording of the questions, please raise hand. If your question is relevant to the entire group, I will repeat it outloud.

Other information about the exam

- When will the exam take place?
  - 17 October 2024, at standard time 17:15 – 19:00h
  - Please try to come a bit earlier if possible (~17:00h)

- Where will the exam take place?
  - Amphitheatre PO 1

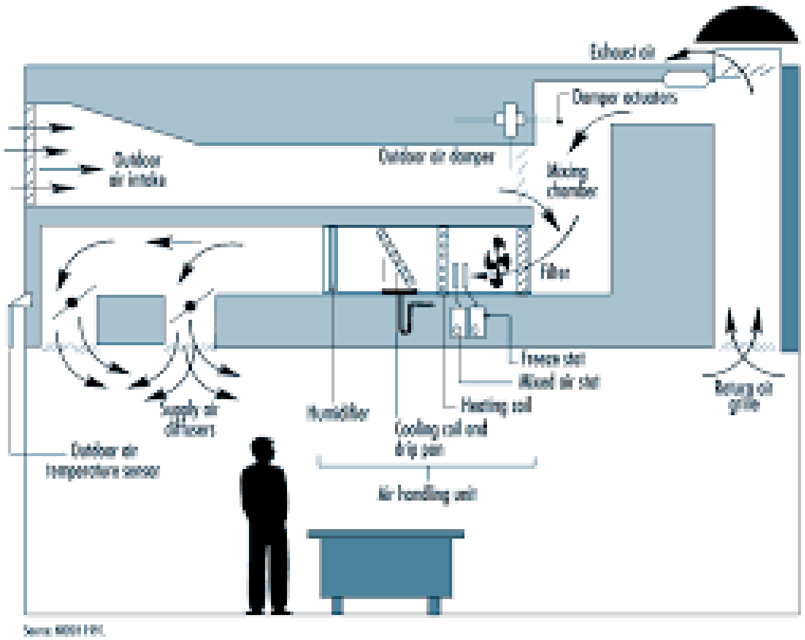


Today’s objectives

- Introduction to HVAC systems
  - Psychometric processes in HVAC systems
  - Examples & exercises

Key functions of HVAC systems

- Thermal comfort
  - Heating or Cooling air
  - Dehumidification of warm and humid
  - Humidification of cold and dry air
- Ventilation (outdoor air)
- Air pollution removal (filtration)



HVAC systems

First stage

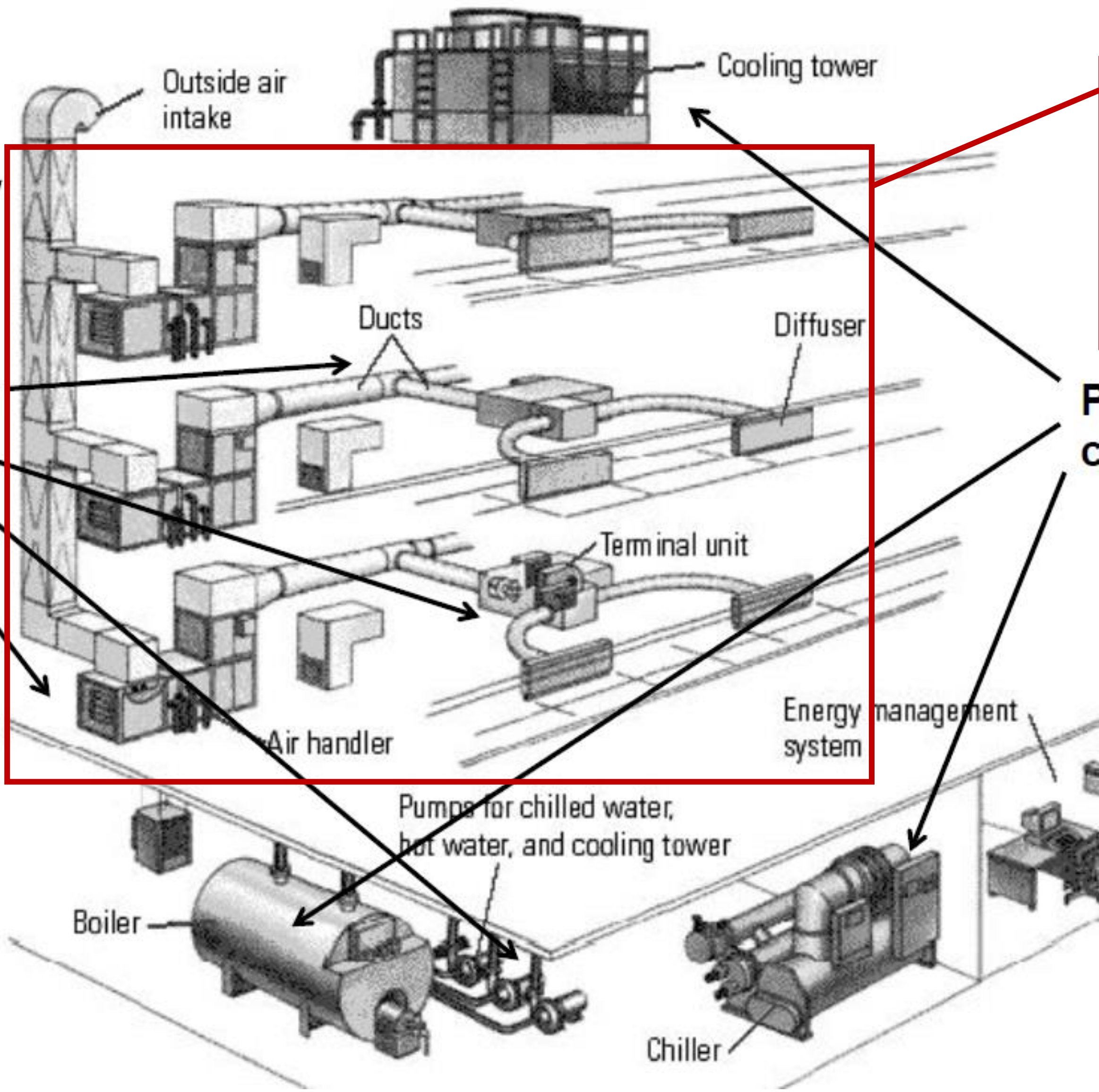
- Chillers and condenser units
- Cooling towers
- Evaporative coolers

Second stage

- Air Handling Units
- Distribution systems
  - both air (focus) and water

Directly responsible for Indoor Climate

Key components of an HVAC system

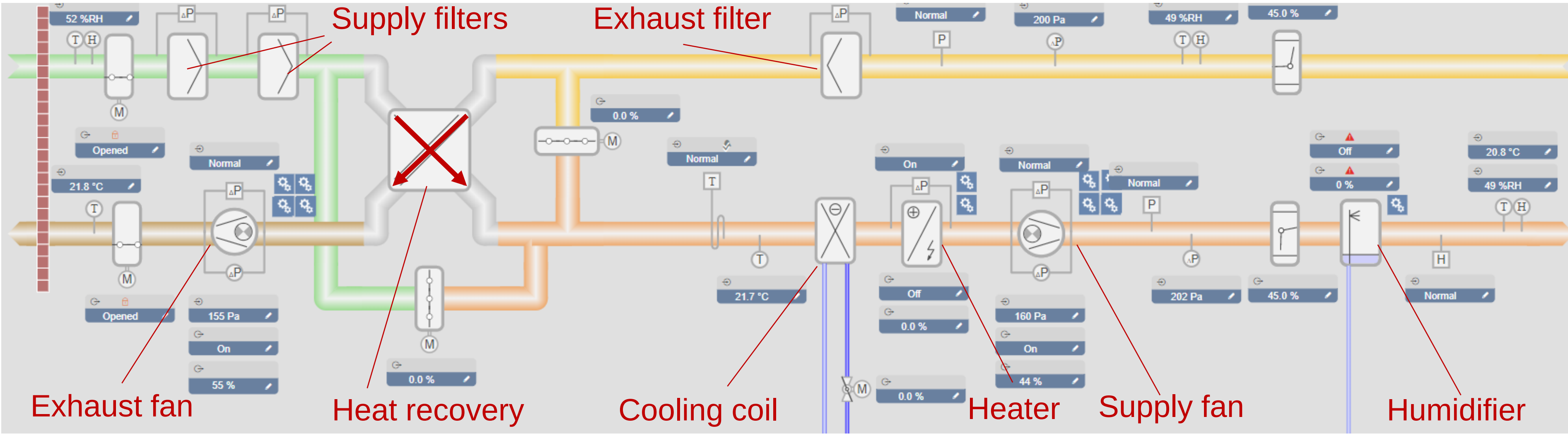


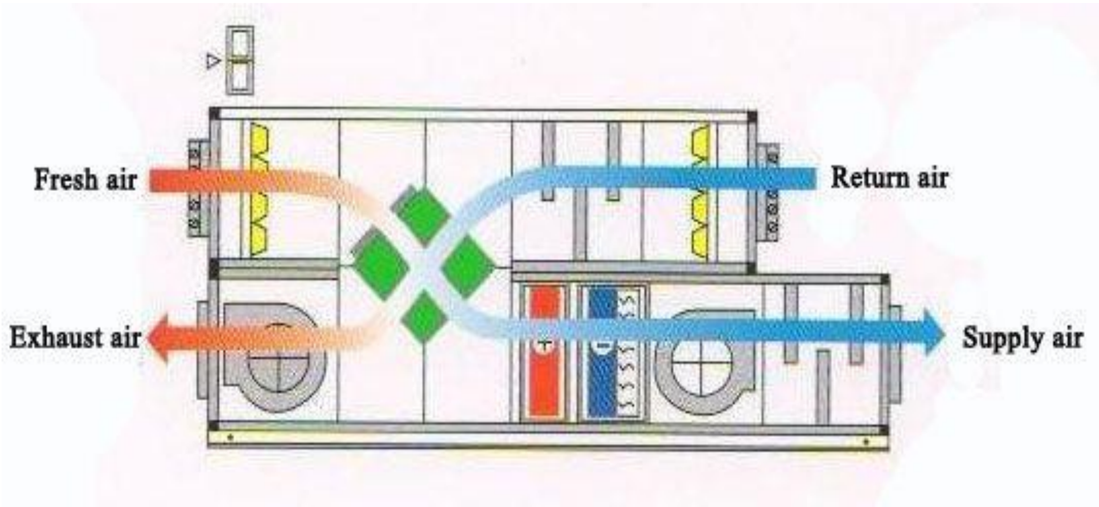
Secondary components

Primary components

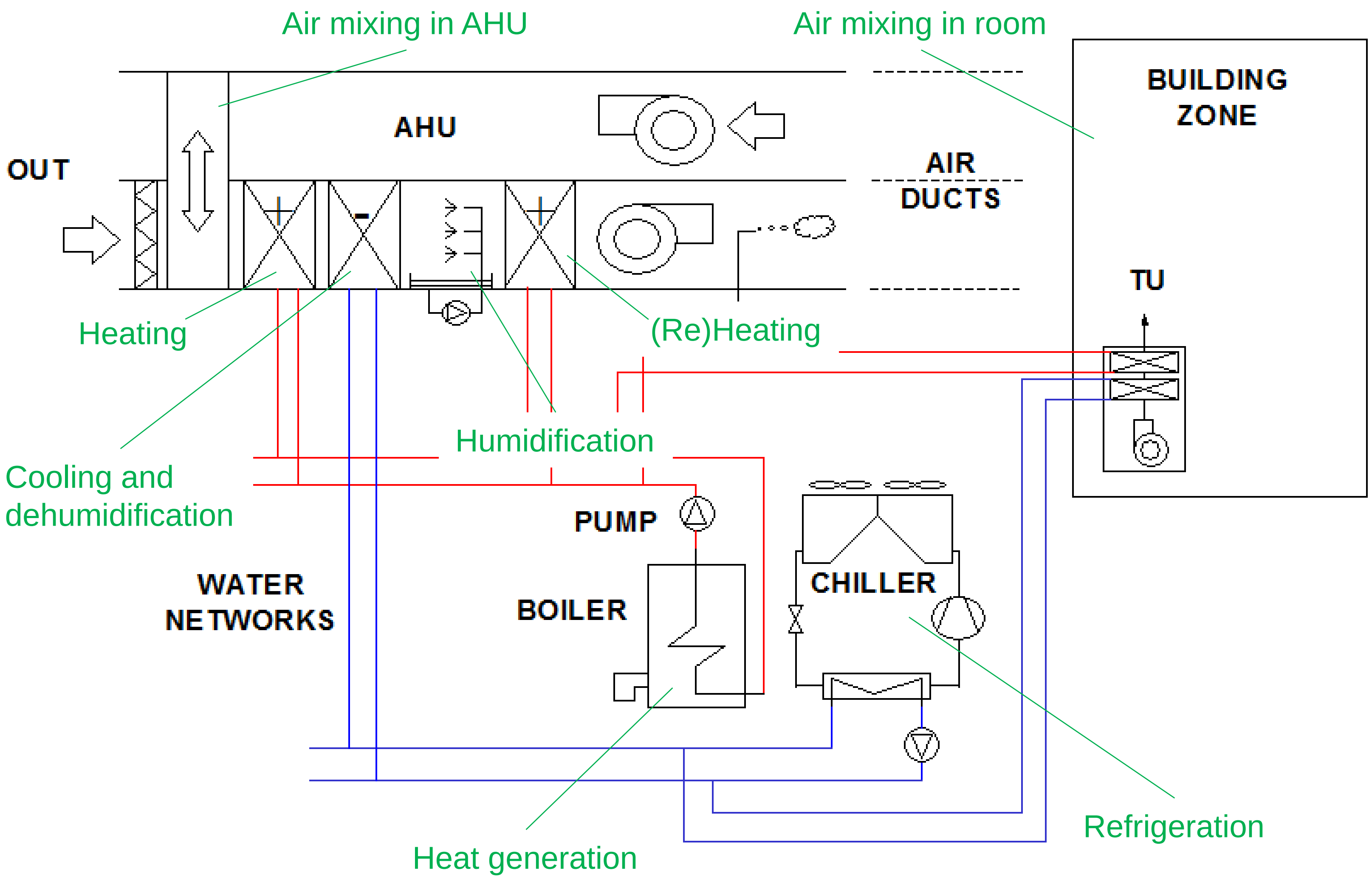
Air Handling Unit, Ducts and Diffusers are the key determinants of indoor climate.

Air Handling Unit (AHU) @ EPFL Fribourg



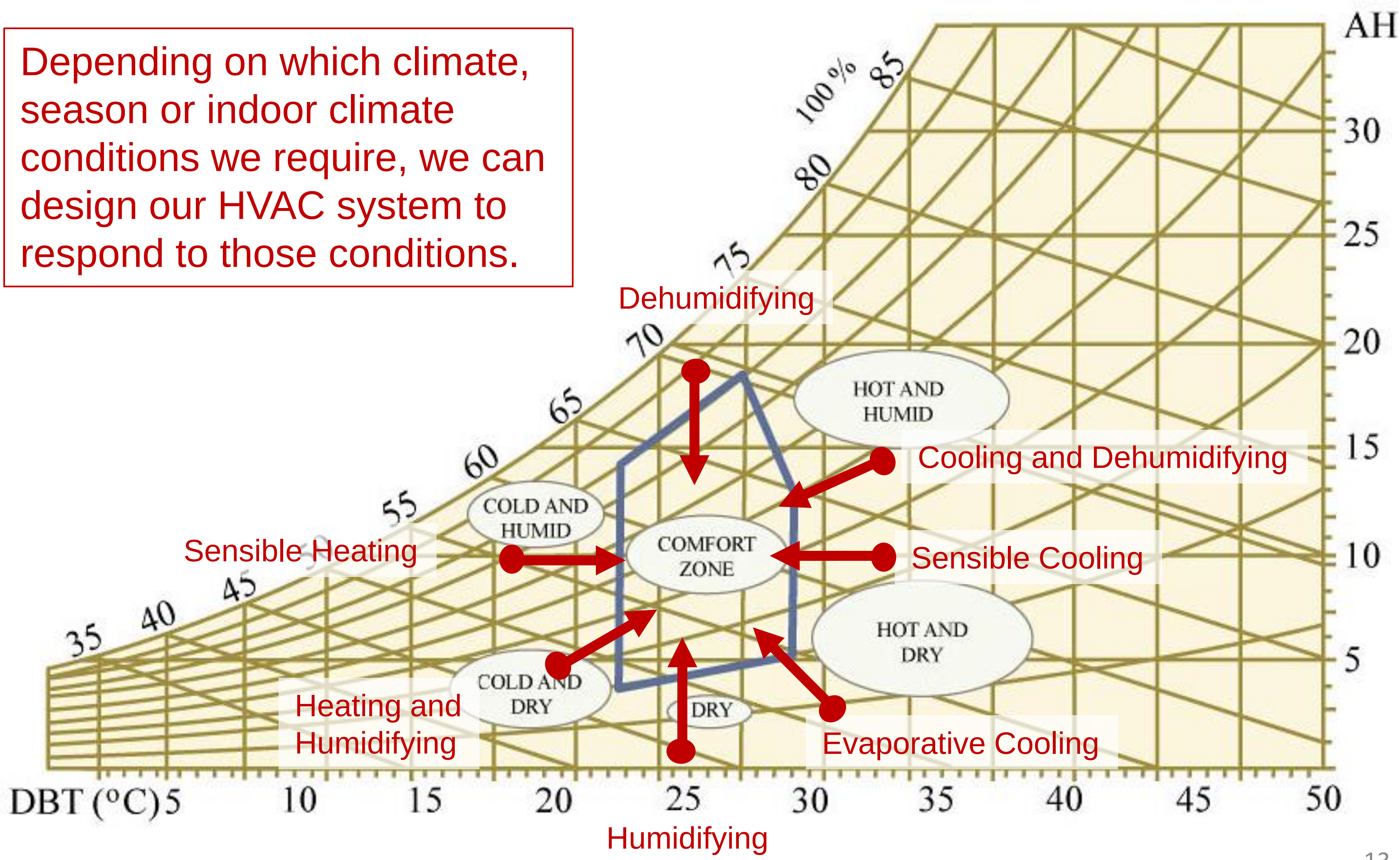


What are the common psychrometric processes?



How do we know which AHU components we need?

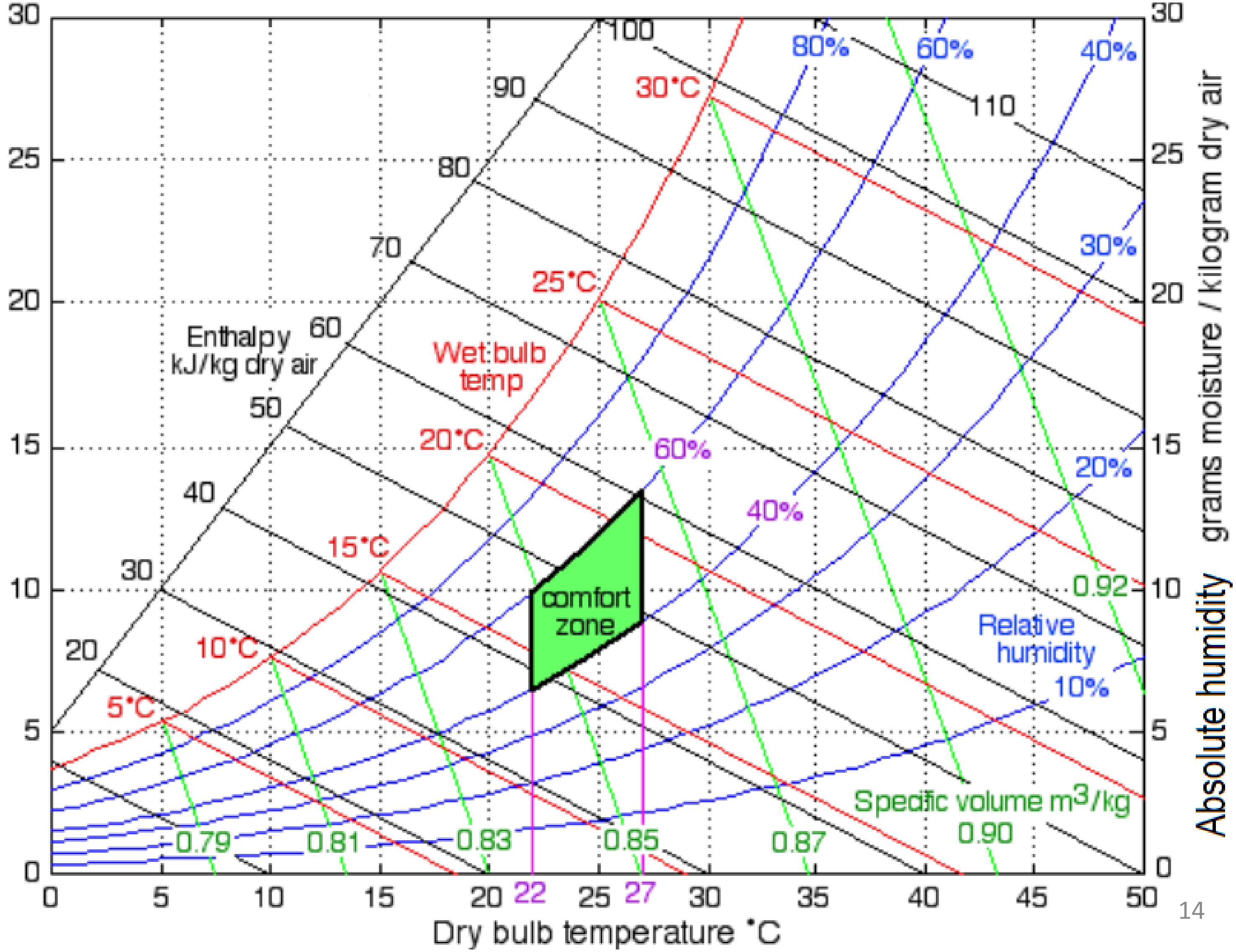
Depending on which climate, season or indoor climate conditions we require, we can design our HVAC system to respond to those conditions.



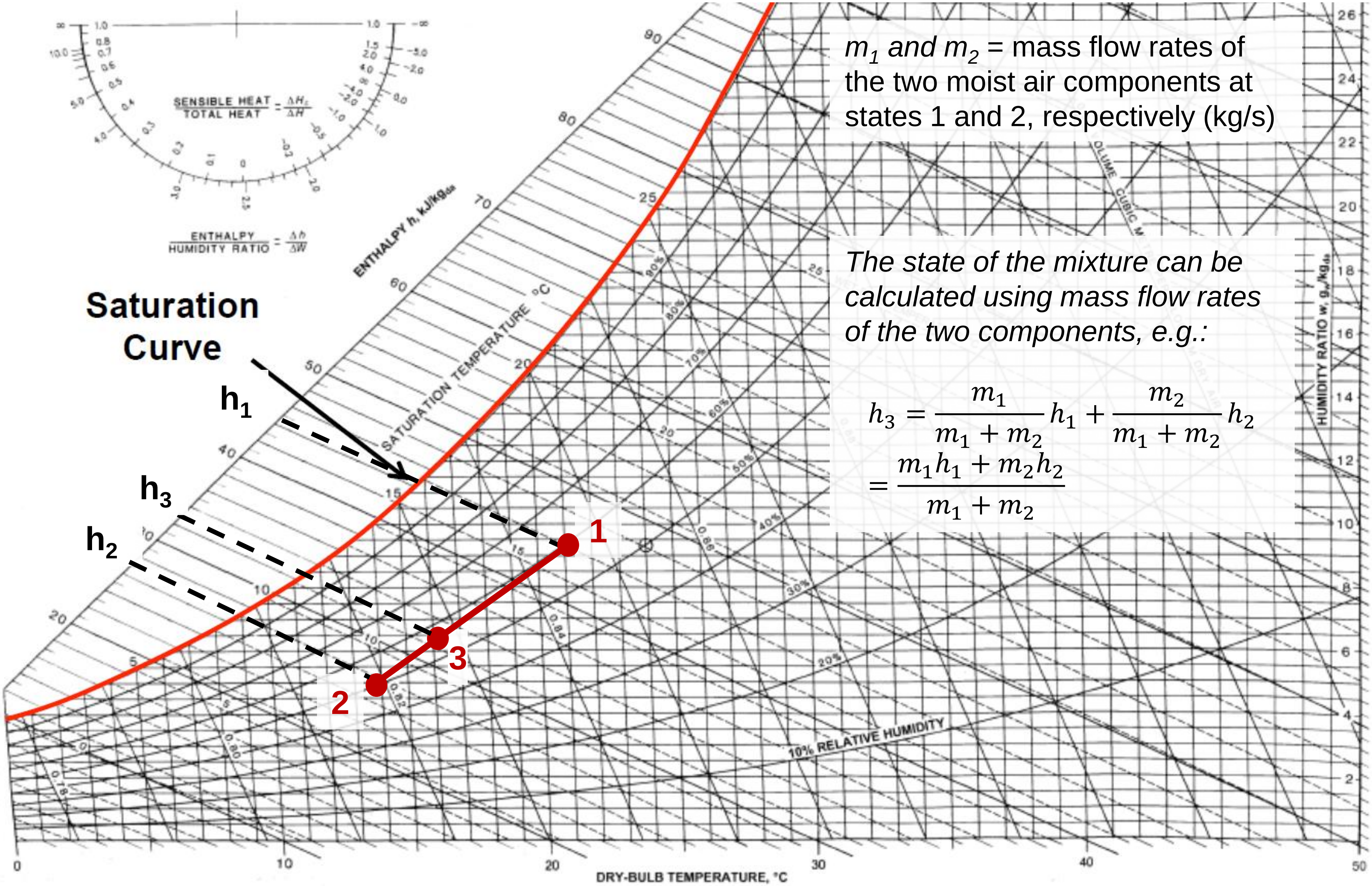
The Psychrometric Chart and Air-Conditioning Processes

To refresh your knowledge on psychometric chart revise Lecture 2 and check out these YouTube videos:

1. https://www.youtube.com/watch?v=BCWnTNNcako
2. https://www.youtube.com/watch?v=s7J6R9wECh8



Mixing two flows of moist air



m_1 and m_2 = mass flow rates of the two moist air components at states 1 and 2, respectively (kg/s)

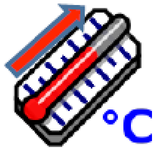
The state of the mixture can be calculated using mass flow rates of the two components, e.g.:

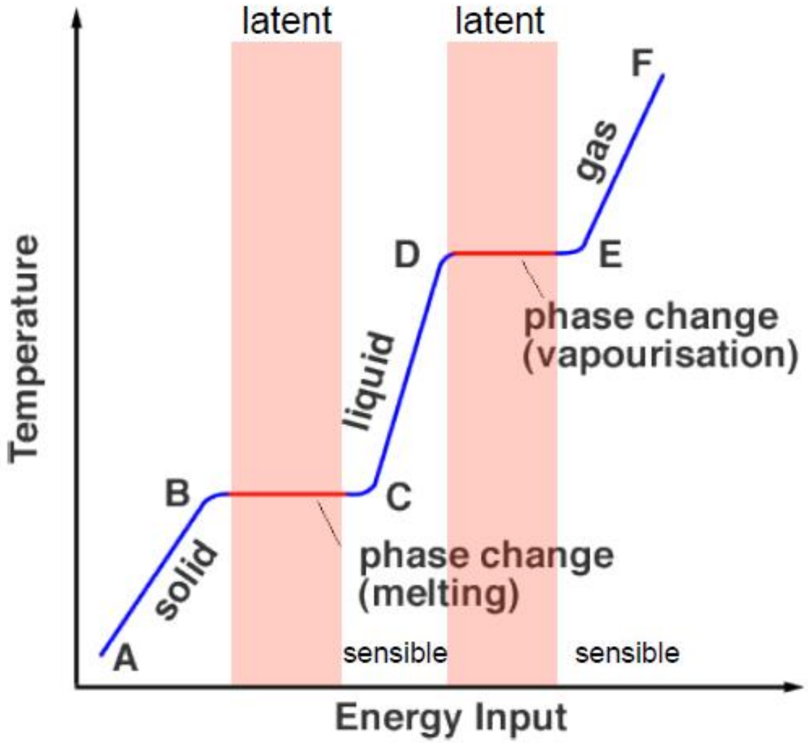
$$h_3 = \frac{m_1}{m_1 + m_2} h_1 + \frac{m_2}{m_1 + m_2} h_2$$

$$= \frac{m_1 h_1 + m_2 h_2}{m_1 + m_2}$$

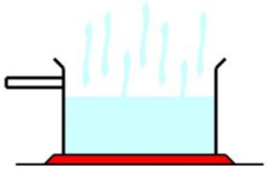
Reminder: Sensible and Latent Heat basics

- Sensible energy
  - Energy used to increase the velocity or vibrations of molecules (i.e., temperature)
  - No phase change





- Latent energy
  - The material-specific amount of energy given off (or taken up) during a state change
  - Solid to liquid: heat of fusion
  - Liquid to gas: heat of vaporization



Generic equations for both heating and cooling processes

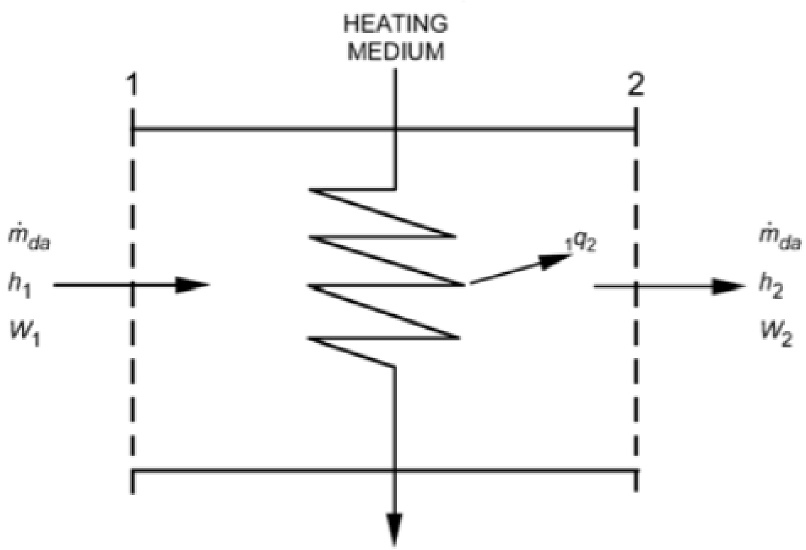


Fig. 2 Schematic of Device for Heating Moist Air

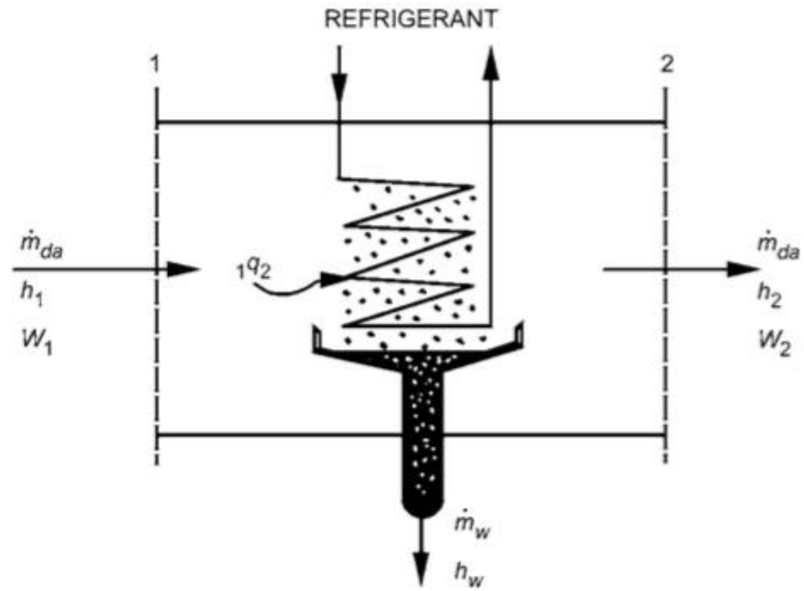


Fig. 3 Schematic of Device for Cooling Moist Air

$$Q_{1\rightarrow 2} = \dot{m}_{da}(h_2 - h_1) \qquad Q_{total} = \dot{m}_{da}(h_{exit} - h_{inlet})$$

$Q_{1\text{-}2}$ = total rate of heat transfer from state 1 to state 2 (W)
m_{da} = mass flow rate of dry air (kg$_{da}$/s)
$h_{exit,2}$ = enthalpy at the exit (J/kg$_{da}$)
$h_{inlet,1}$ = enthalpy at the inlet (J/kg$_{da}$)

Sensible and Latent heat transfer equations

$$Q_{sensible} = \dot{m}_{da} C_p (T_{exit} - T_{inlet}) = \rho_{da} \dot{V}_{da} C_p (T_{exit} - T_{inlet})$$

$Q_{sensible}$ = rate of sensible heat transfer (W)
C_p = specific heat of air (J/kgK)
ρ_{da} = dry air density (kg/m^3)
T_{inlet} = inlet temperature (K or °C)
T_{exit} = exit temperature (K or °C)

For heating: $Q_{sensible} > 0$

For cooling: $Q_{sensible} < 0$

$$Q_{latent} = \dot{m}_{da} h_{fg} (W_{exit} - W_{inlet}) = \rho_{da} \dot{V}_{da} h_{fg} (W_{exit} - W_{inlet})$$

Q_{latent} = rate of latent heat transfer (W)
h_{fg} = enthalpy, or latent heat, of vaporization (J/kg)
* h_{fg} = 2260 kJ/kg for water
W_{inlet} = inlet humidity ratio (kg$_w$/kg$_{da}$)
W_{exit} = exit humidity ratio (kg$_w$/kg$_{da}$)

For humidification:
$Q_{latent} > 0$

For dehumidification:
$Q_{latent} < 0$

Example: Sensible heating (*or cooling*)

Air, saturated at 3 °C, enters a heating coil at a rate of 7’000 kg/s and air leaves the coil at 32 °C

- What is the added enthalpy?
- What is the rate of heat addition (Q)?

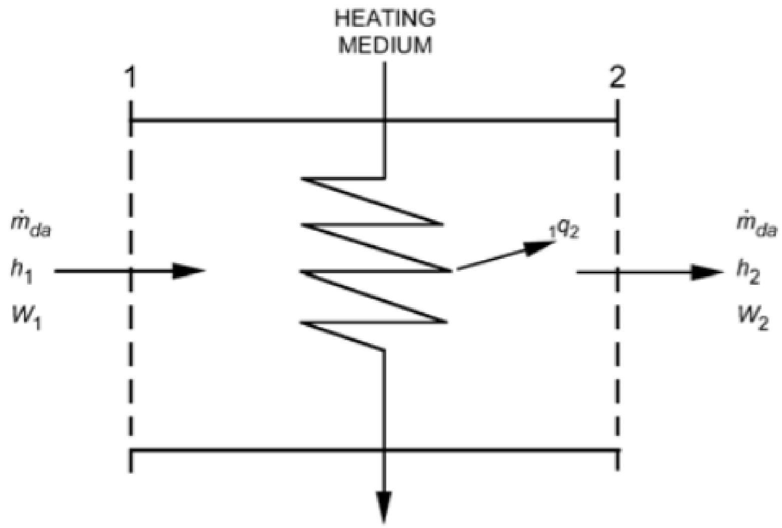
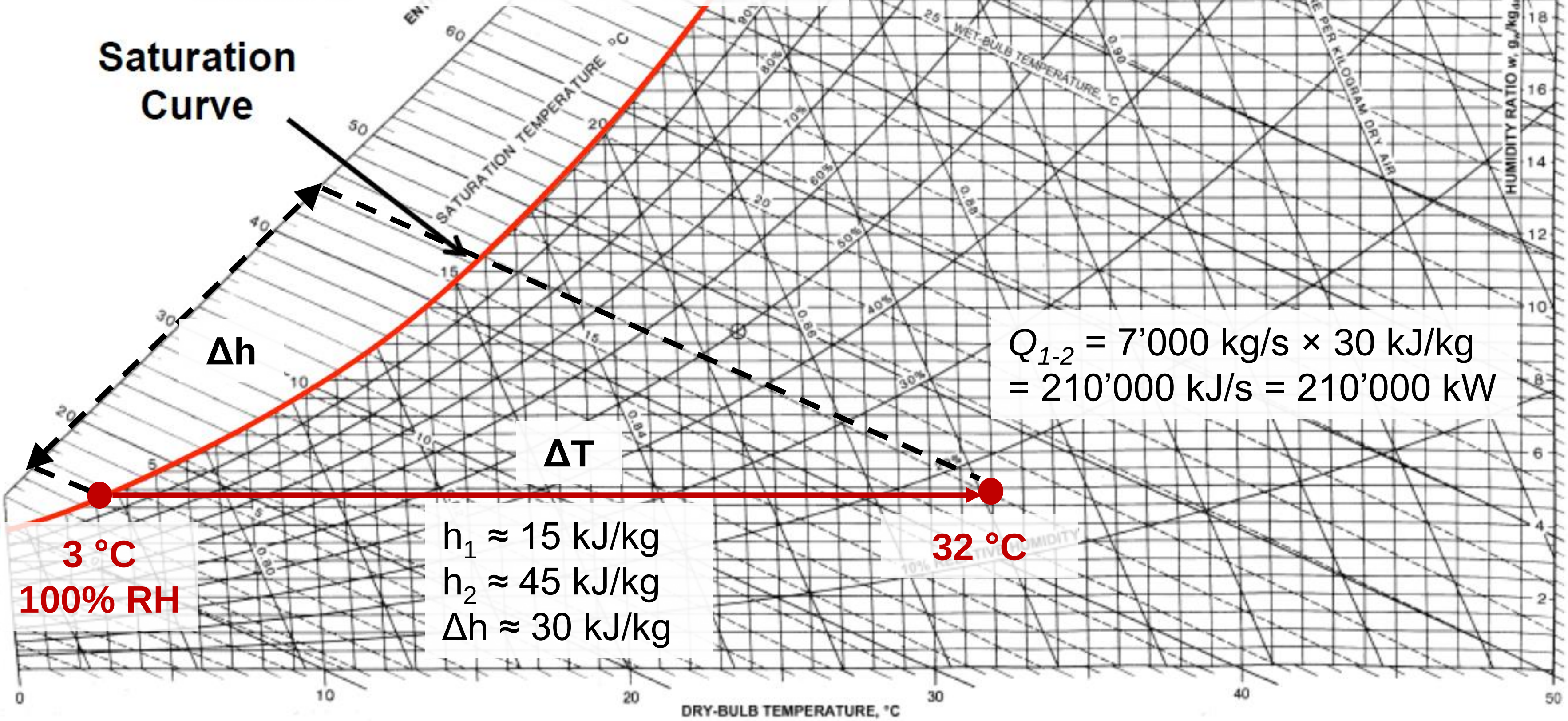


Fig. 2 Schematic of Device for Heating Moist Air

Sensible heating of warm & humid air

$$Q_{1\rightarrow 2} = \dot{m}_{da}(h_2 - h_1)$$

$Q_{1\text{-}2}$ = total rate of heat transfer from state 1 to state 2 (W)
m_{da} = mass flow rate of dry air (kg_{da}/s)
$h_{exit,2}$ = enthalpy at the exit (J/kg_{da})
$h_{inlet,1}$ = enthalpy at the inlet (J/kg_{da})

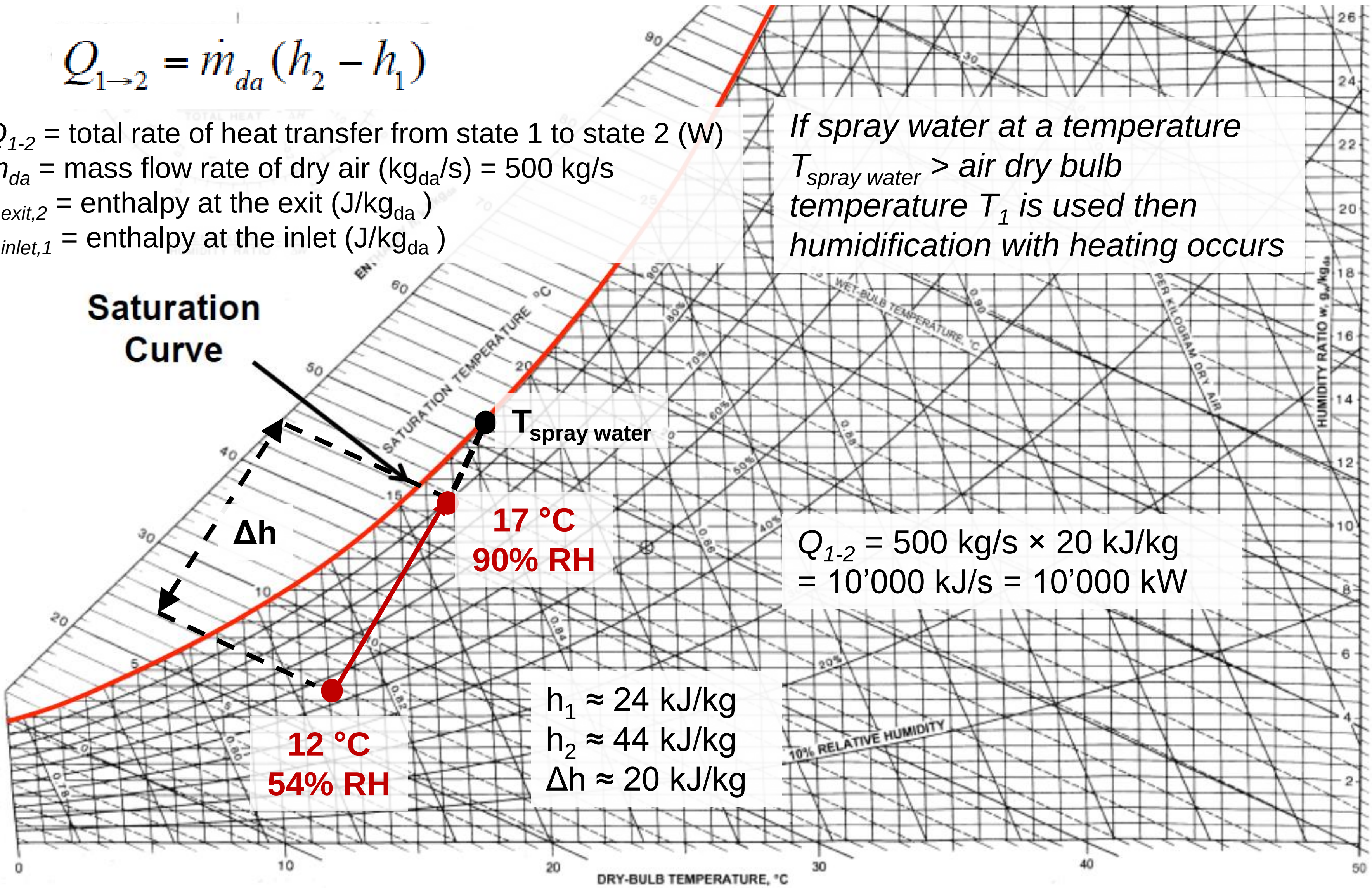


Example: Humidification with heating

$$Q_{1\to2} = \dot{m}_{da}(h_2 - h_1)$$

$Q_{1\text{-}2}$ = total rate of heat transfer from state 1 to state 2 (W)
m_{da} = mass flow rate of dry air (kg_{da}/s) = 500 kg/s
$h_{exit,2}$ = enthalpy at the exit (J/kg_{da})
$h_{inlet,1}$ = enthalpy at the inlet (J/kg_{da})

If spray water at a temperature $T_{spray\ water}$ > air dry bulb temperature T_1 is used then humidification with heating occurs

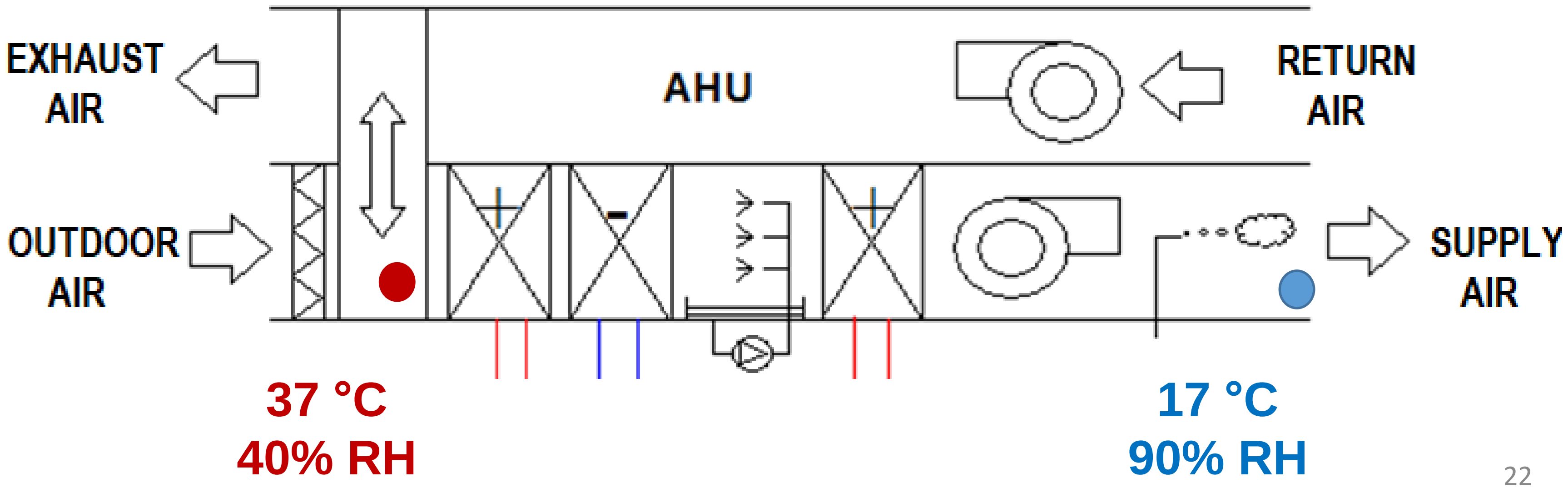


$Q_{1\text{-}2}$ = 500 kg/s × 20 kJ/kg
= 10’000 kJ/s = 10’000 kW

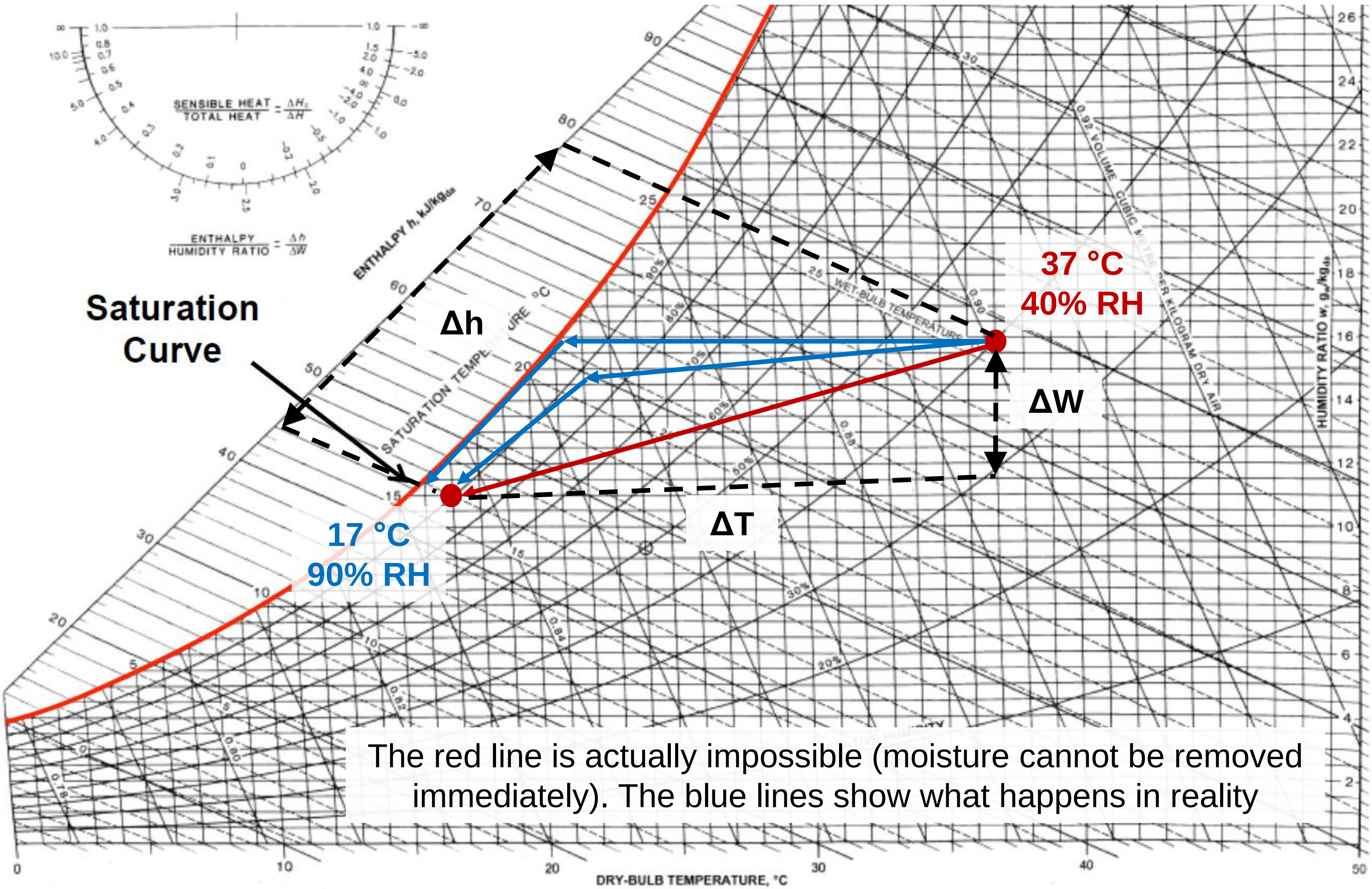
h_1 ≈ 24 kJ/kg
h_2 ≈ 44 kJ/kg
Δh ≈ 20 kJ/kg

Cooling and dehumidification of warm & humid air

Example: Air flowing over a cooling coil
• Removing both moisture and heat
– Sensible + latent cooling



Cooling and dehumidification of warm & humid air

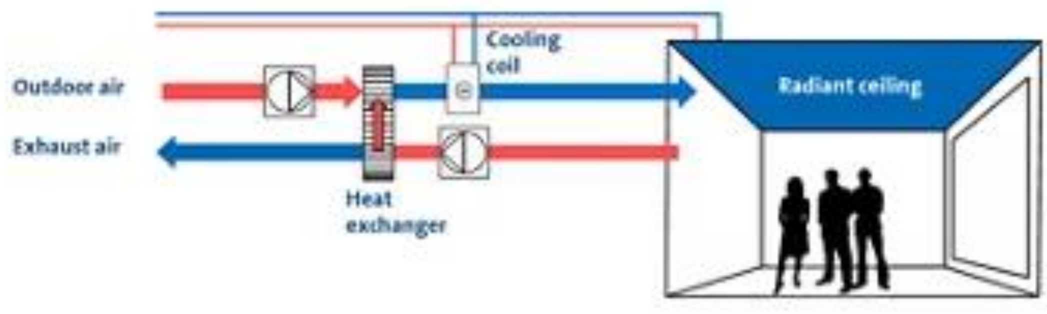


The red line is actually impossible (moisture cannot be removed immediately). The blue lines show what happens in reality

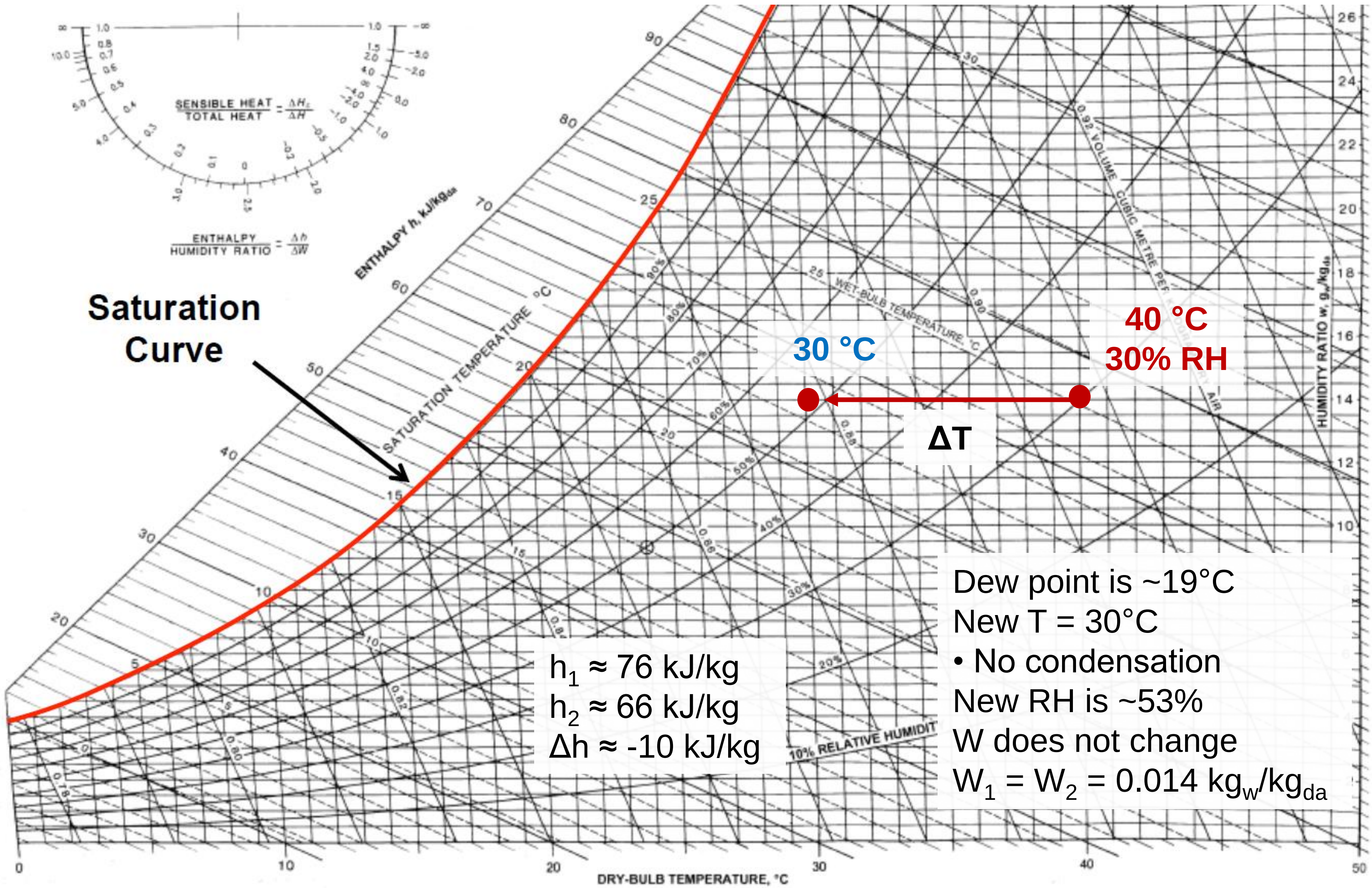
Example: Sensible cooling

Radiant ceiling panes cool the moist air from 40°C and 30% RH to 30°C without condensation

– What is the RH at W at the process end point?



Cooling and dehumidification of warm & humid air

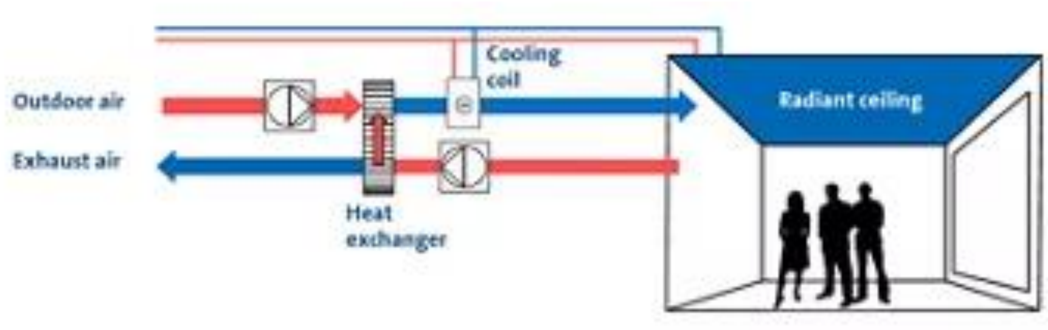


Example: Sensible + latent cooling

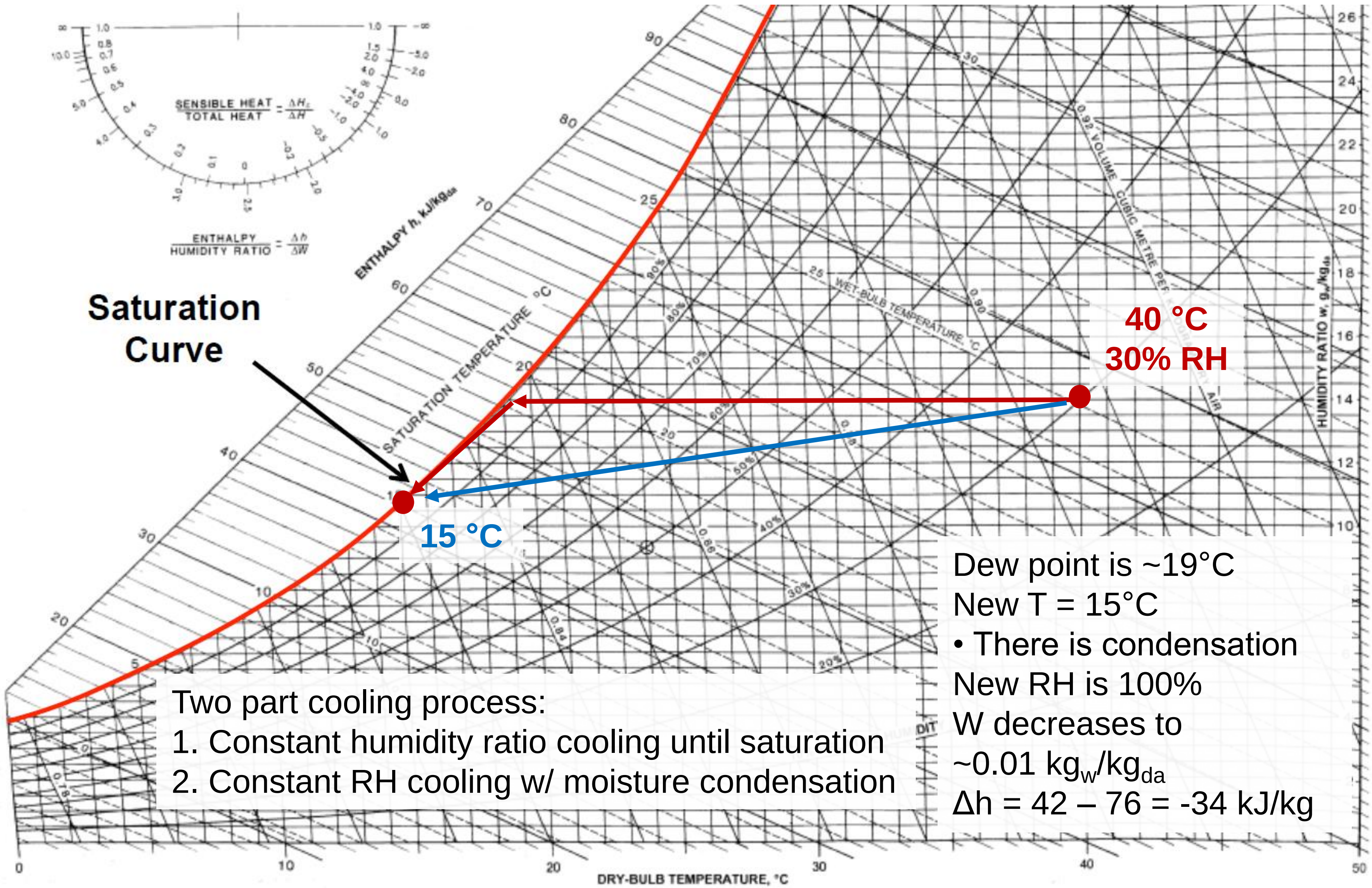
Radiant ceiling panes cool the moist air from 40°C and 30% RH to 15°C.

– Does the water vapor condense?

– What is the RH at W at the process end point?



Cooling and dehumidification of warm & humid air



Two part cooling process:

1. Constant humidity ratio cooling until saturation
2. Constant RH cooling w/ moisture condensation

Dew point is ~19°C

New T = 15°C

- There is condensation

New RH is 100%

W decreases to ~0.01 kg_w/kg_{da}

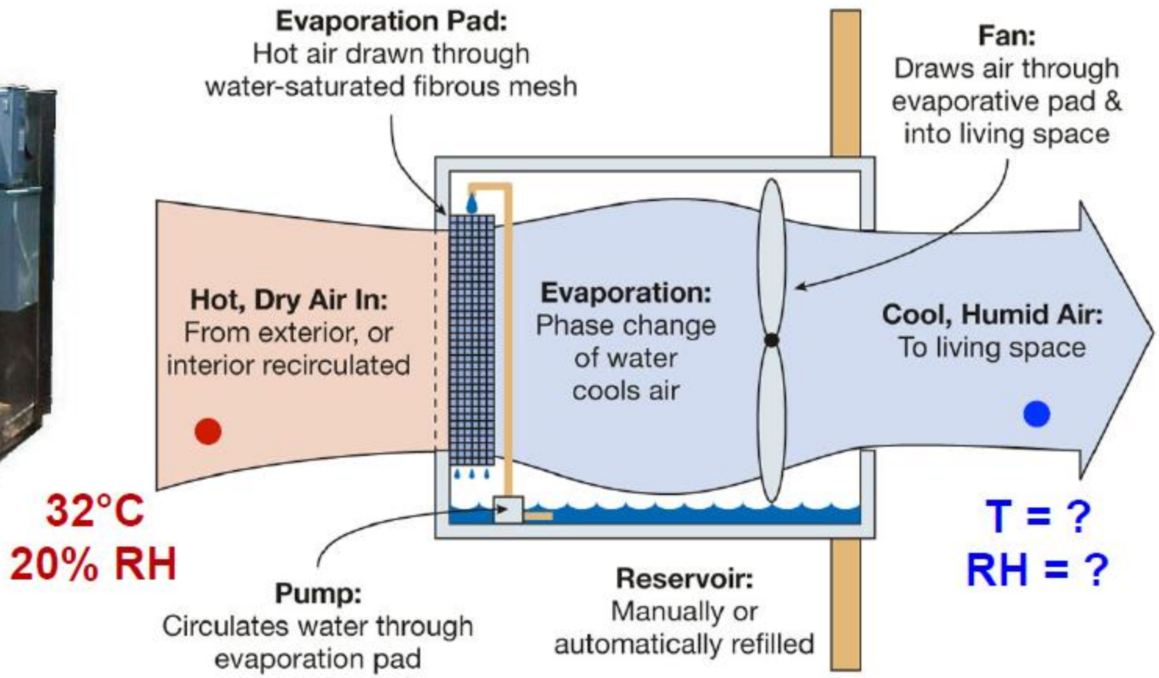
$\Delta h = 42 – 76 = -34$ kJ/kg

Example: Evaporative cooling

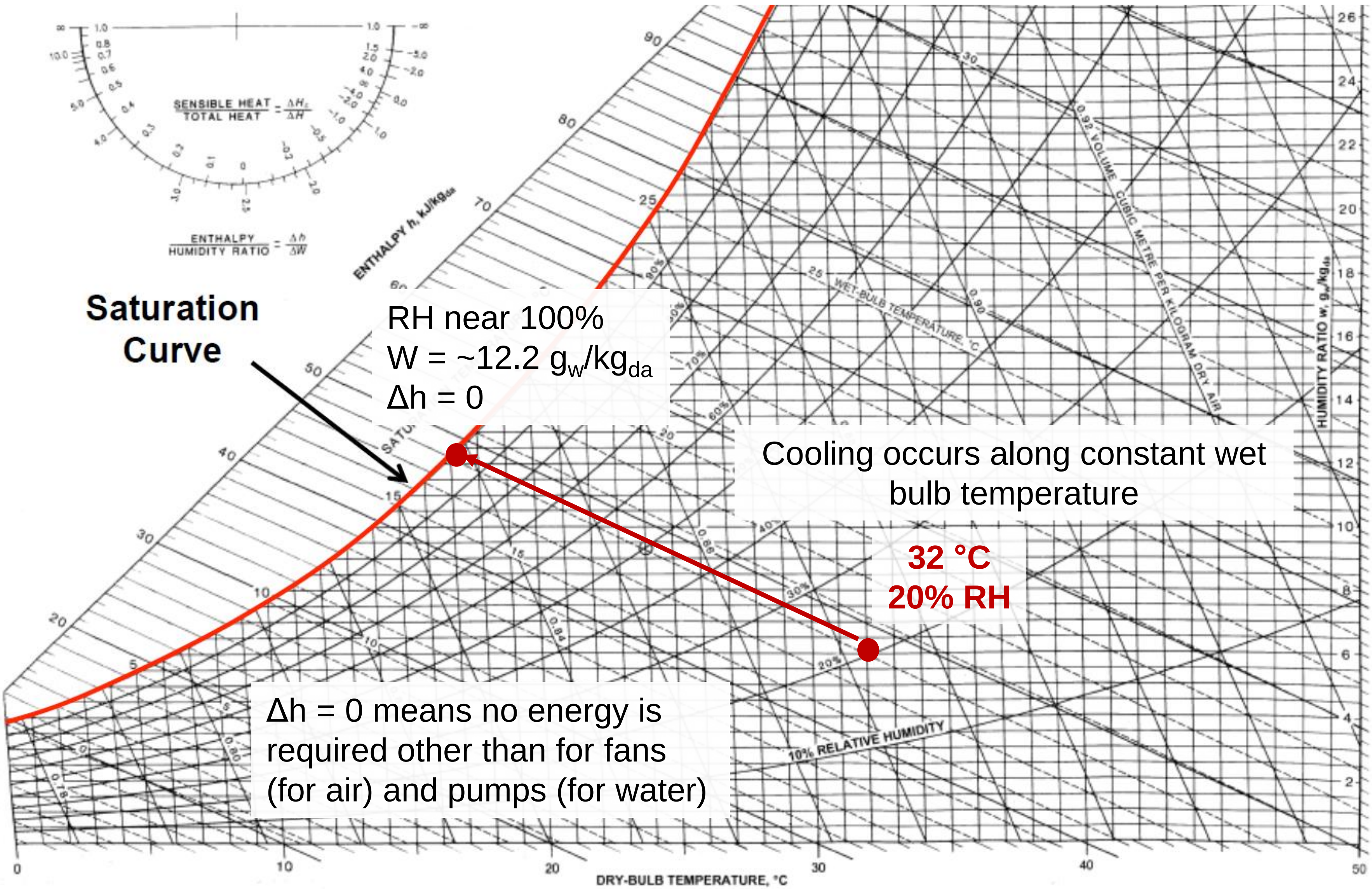
Hot, dry outdoor air is cooled with an evaporative cooler, or “swamp cooler”

– What is the T, RH, and W of the supply air?

– Why would we choose this system?



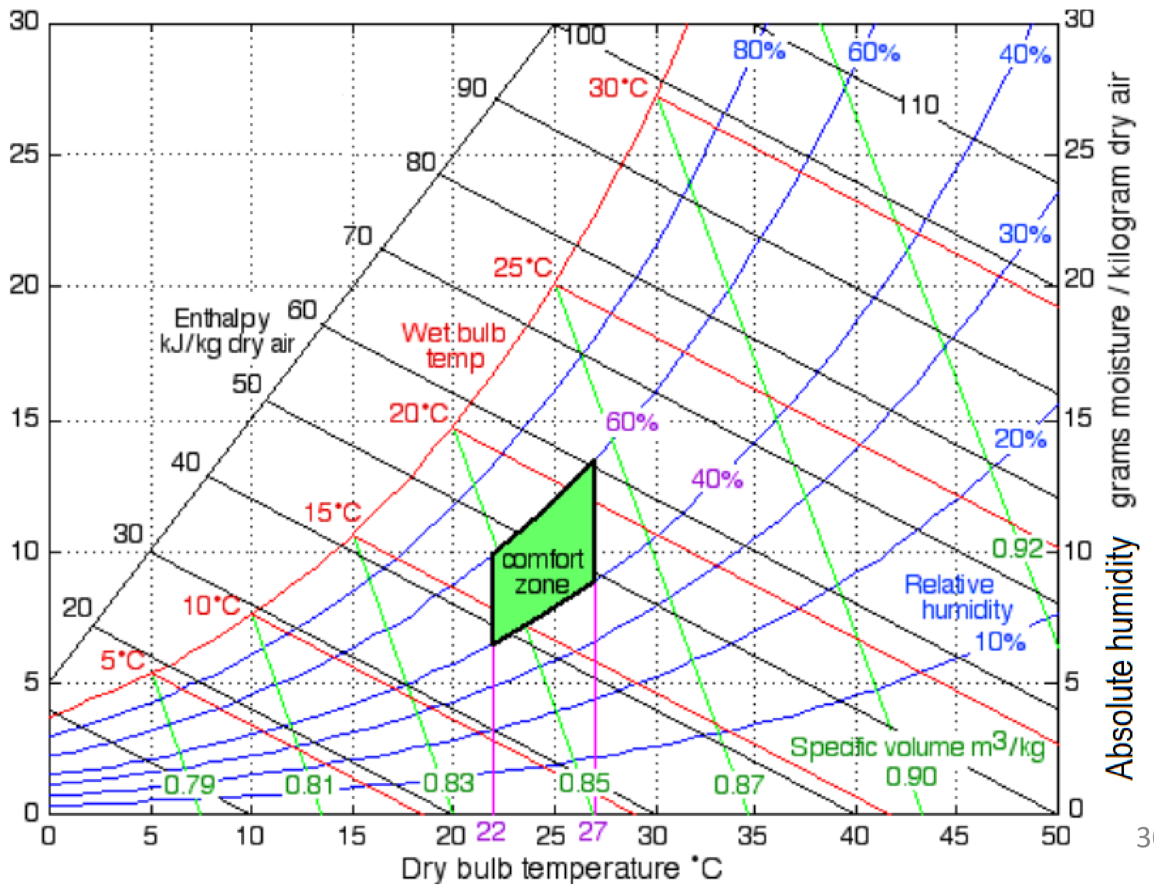
Evaporative cooling



In-class exercise #1

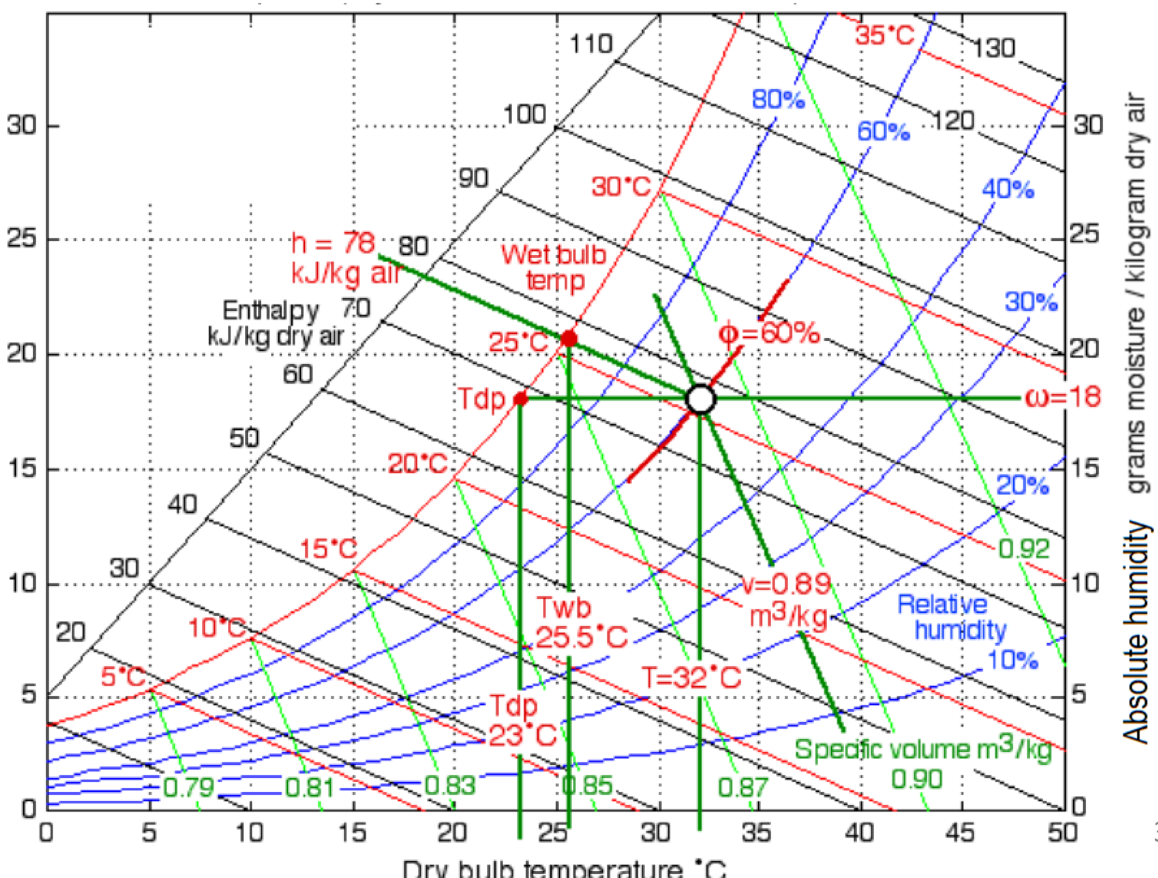
Assume that the outside air temperature is 32°C with a relative humidity is 60%. Use the psychrometric chart to determine the absolute humidity, the enthalpy h, the wet-bulb temperature T_{wb}, the dew-point temperature T_{dp}, and the specific volume of the dry air v. Indicate all the values determined on the chart.

You can download the chart here:
https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf



In-class exercise #1: Solutions

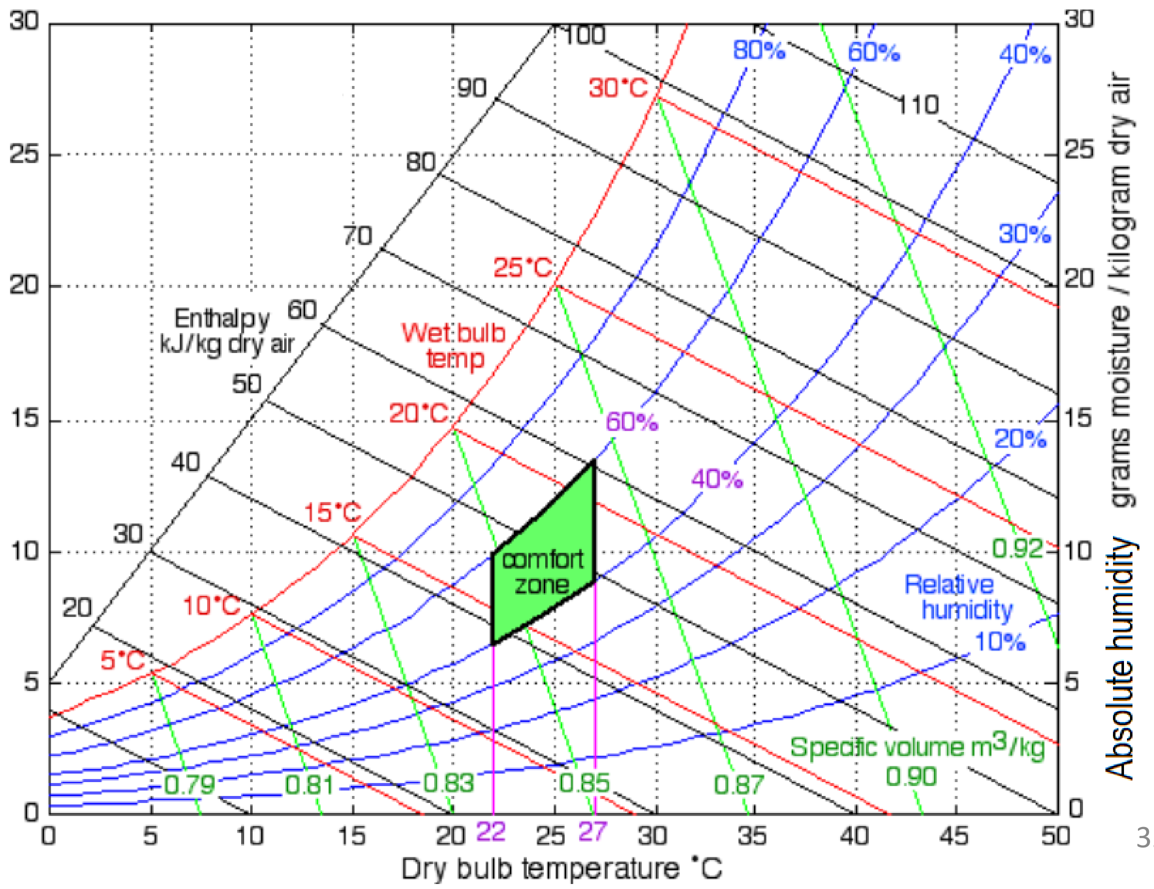
Assume that the outside air temperature is 32°C with a relative humidity is 60%. Use the psychrometric chart to determine the absolute humidity [18 gram-moisture/kg-air], the enthalpy h [78 kJ/kg-air], the wet-bulb temperature T_{wb} [25.5°C], the dew-point temperature T_{dp} [23°C], and the specific volume of the dry air v [0.89 m^3/kg]. Indicate all the values determined on the chart.



In-class exercise #2

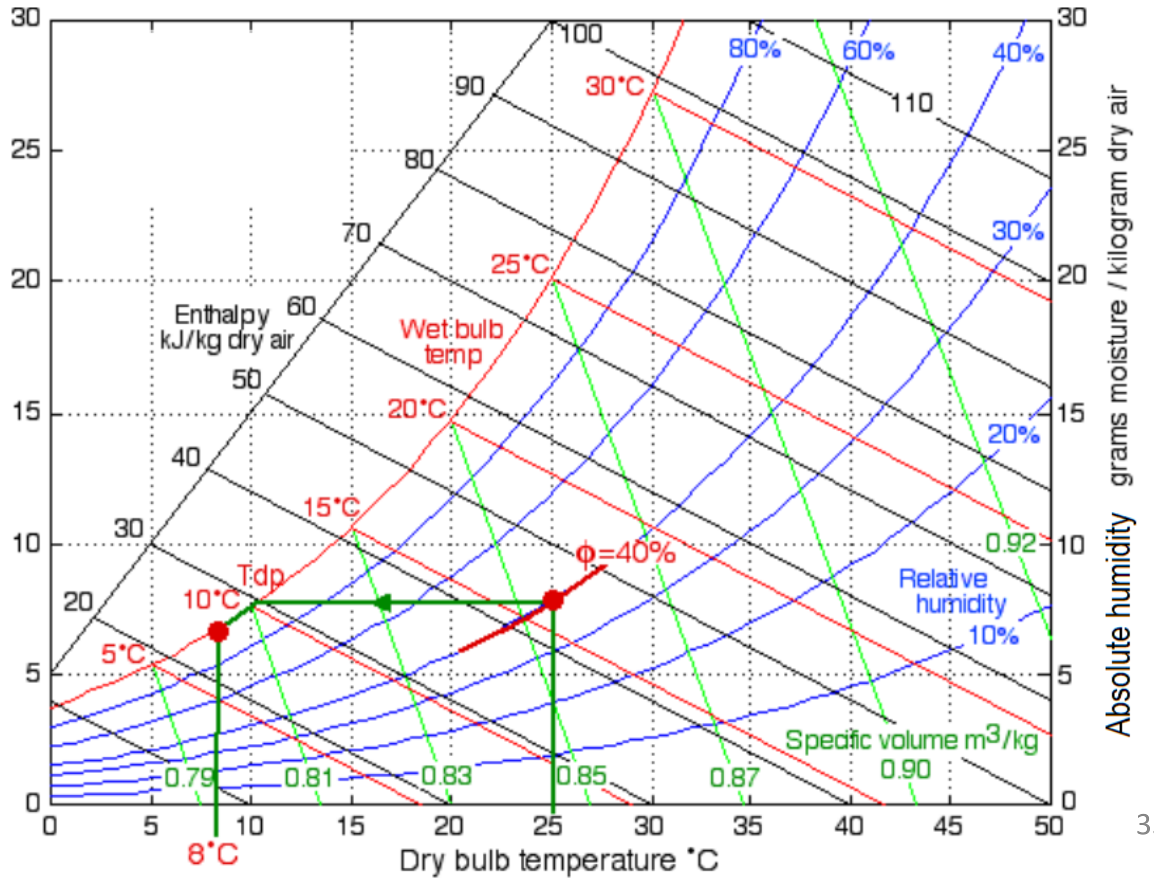
Assume that the outside air temperature is 8°C. If the air in a room is at 25°C with a relative humidity 40%. Use the psychrometric chart to determine if the windows of that room which are in contact with the outside will become foggy.

You can download the chart here: https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf



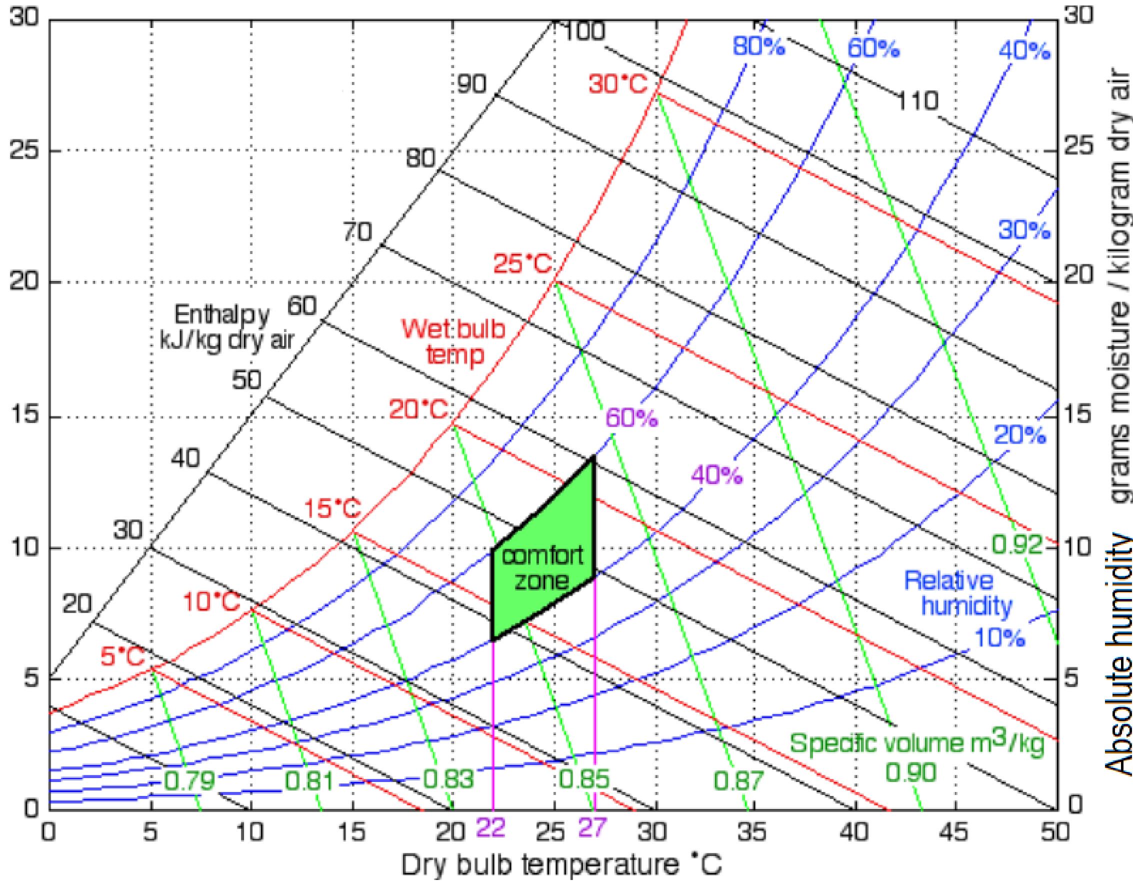
In-class exercise #2: Solutions

The indoor air in contact with the windows will become colder until the dew point is reached. Notice that under the conditions of 25°C and 40% relative humidity the dew point temperature is slightly higher than 10°C. At that point the water vapor condenses as the temperature approaches 8°C along the saturation line, and the windows will become foggy.



In-class exercise #3

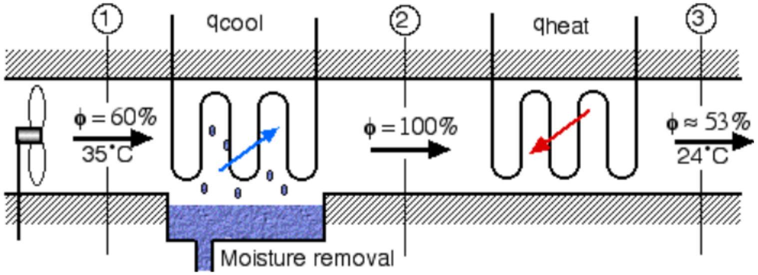
Outside air at 35°C and 60% relative humidity is to be conditioned by cooling and heating so as to bring the air to within the "comfort zone“ (assume 25°C and 50%). Using the Psychrometric Chart plot the required air conditioning process and estimate (a) the amount of moisture removed, (b) the heat (enthalpy) removed, and (c) the amount of heat (enthalpy) added.

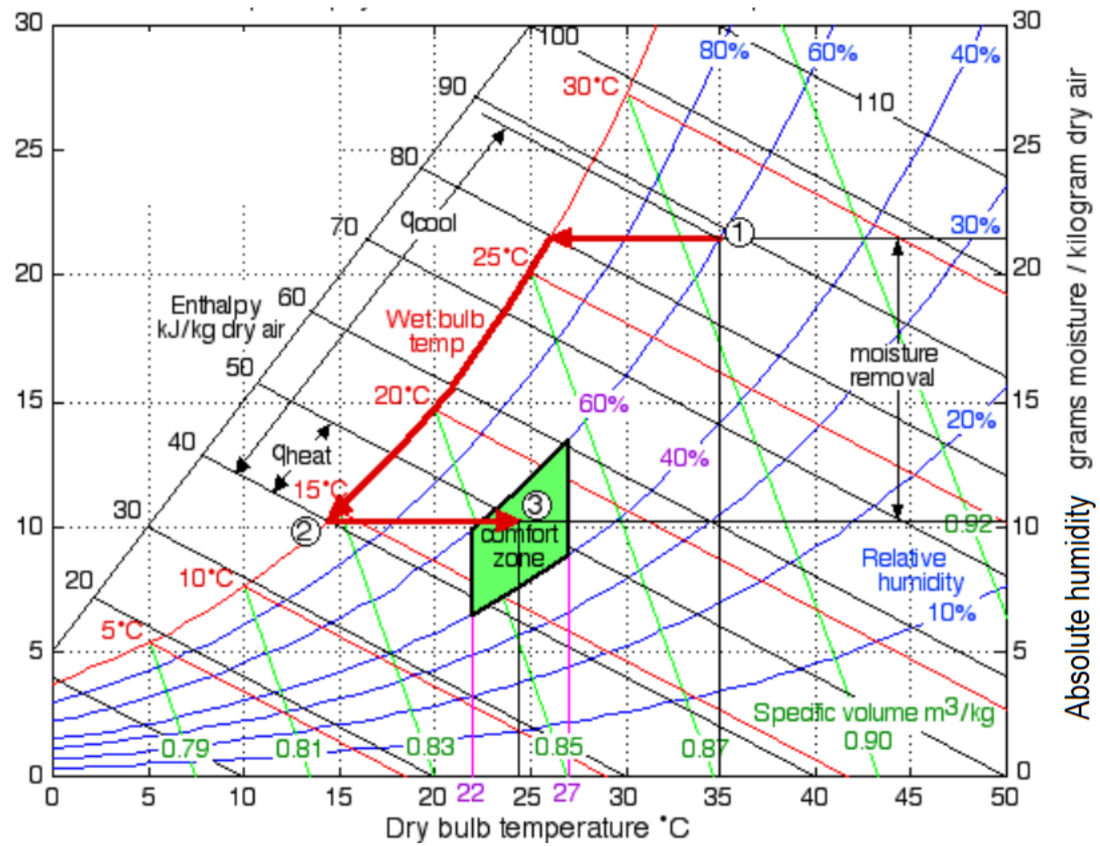


You can download the chart here: https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf

In-class exercise #3: Solutions

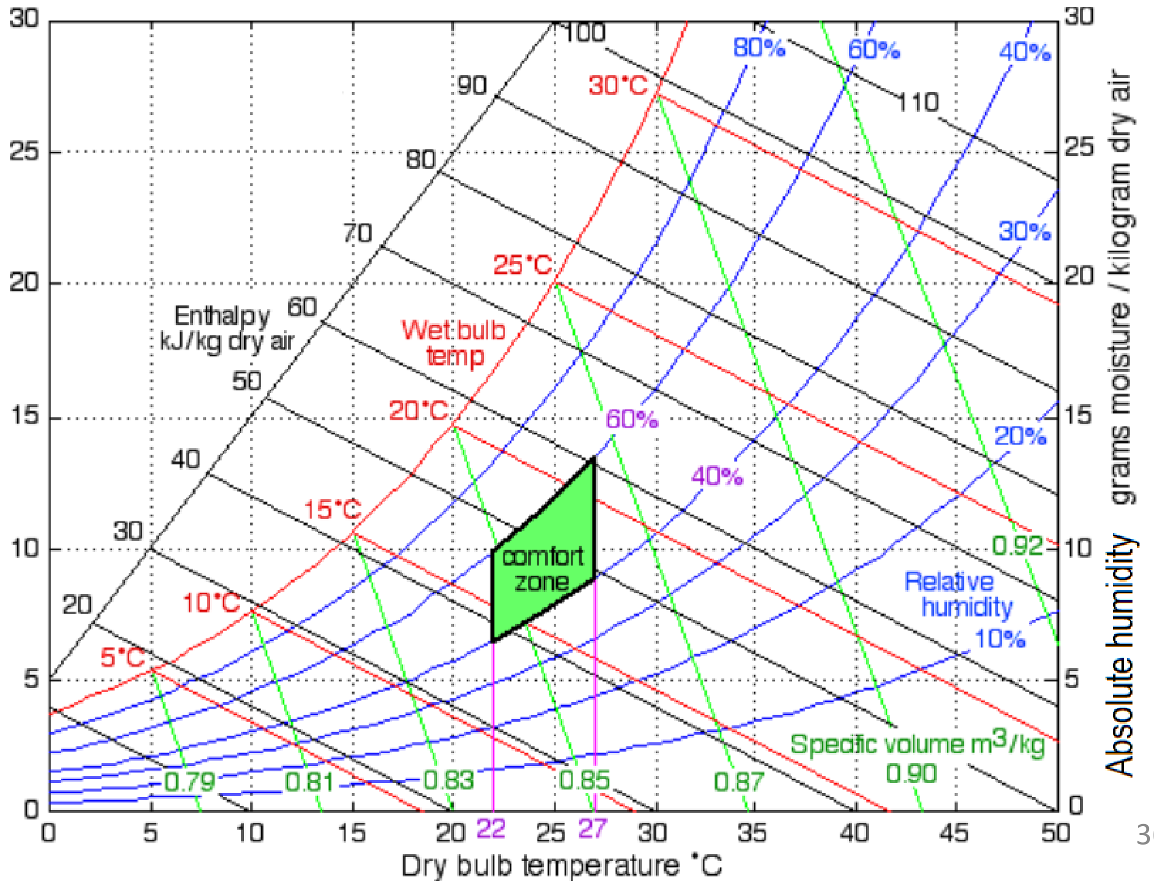
Outside air at 35°C and 60% relative humidity is to be conditioned by cooling and heating so as to bring the air to within the "comfort zone". Using the Psychrometric Chart neatly plot the required air conditioning process and estimate (a) the amount of moisture removed [11.5g-H_20/kg-dry-air], (b) the heat removed [(1)-(2), h_{cool} = 48kJ/kg-dry-air], and (c) the amount of heat added [(2)-(3), h_{heat} = 10kJ/kg-dry-air].





In-class exercise #4

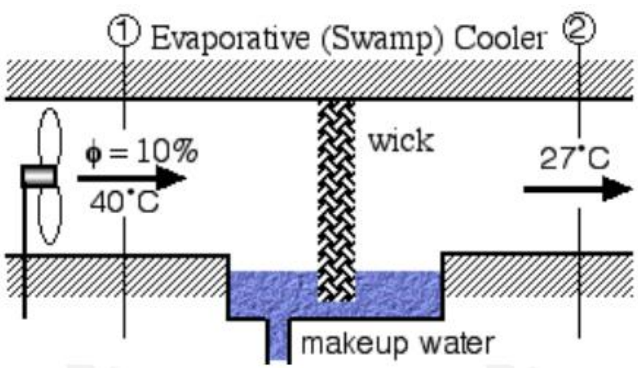
Hot dry air at 40°C and 10% relative humidity passes through an evaporative cooler (enthalpy is constant). Water is added as the air passes through a series of wicks and the mixture exits at 27°C. Using the psychrometric chart determine (a) the outlet relative humidity, (b) the amount of water added, and (c) the lowest temperature that could be realized.

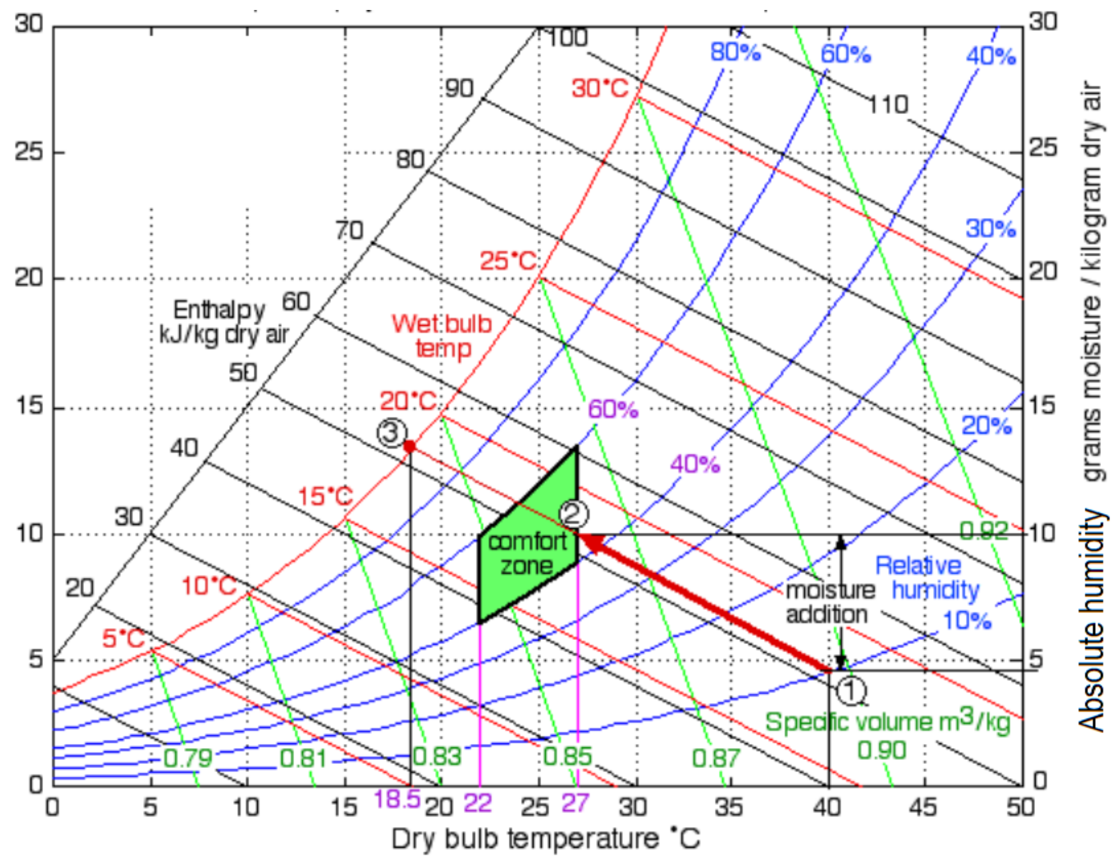


You can download the chart here: https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf

In-class exercise #4: Solutions

Hot dry air at 40°C and 10% relative humidity passes through an evaporative cooler. Water is added as the air passes through a series of wicks and the mixture exits at 27°C. Using the psychrometric chart determine (a) the outlet relative humidity [45%], (b) the amount of water added [5.4g-H_20/kg-dry-air], and (c) the lowest temperature that could be realized [18.5°C].





Homework #1

Why buildings in hot and humid climate (e.g., in Singapore) are being overcooled?

E.g., Hot and humid outdoor air in Singapore is typically at 33°C and 18 g/kg absolute humidity.

Next time…

- Midterm exam
  - Good luck and let me know if you have any questions (you should post them on Moodle Forum)

- In 2 weeks we start with Indoor Air Quality
  - Perceived air quality
  - Physical air quality