Thermodynamics: An Engineering Approach, 6th Edition
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McGraw-Hill, 2008

Chapter 14
GAS–VAPOR MIXTURES AND AIR-CONDITIONING

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Objectives

- Differentiate between *dry air* and *atmospheric air*.
- Define and calculate the specific and relative humidity of atmospheric air.
- Calculate the dew-point temperature of atmospheric air.
- Relate the adiabatic saturation temperature and wet-bulb temperatures of atmospheric air.
- Use the psychrometric chart as a tool to determine the properties of atmospheric air.
- Apply the principles of the conservation of mass and energy to various air-conditioning processes.

DRY AND ATMOSPHERIC AIR

Atmospheric air: Air in the atmosphere containing some water vapor (or *moisture*).

Dry air: Air that contains no water vapor.

Water vapor in the air plays a major role in human comfort. Therefore, it is an important consideration in air-conditioning applications.

$$h_{\text{dry air}} = c_p T = (1.005\ \text{kJ/kg}\cdot{}^\circ\text{C})T \qquad (\text{kJ/kg})$$

$$\Delta h_{\text{dry air}} = c_p \Delta T = (1.005\ \text{kJ/kg}\cdot{}^\circ\text{C})\ \Delta T \qquad (\text{kJ/kg})$$

Water vapor in air behaves as if it existed alone and obeys the ideal-gas relation $Pv = RT$. Then the atmospheric air can be treated as an ideal-gas mixture:

$$P = P_a + P_v \qquad (\text{kPa})$$

P_a Partial pressure of dry air

P_v Partial pressure of vapor (vapor pressure)

DRY AIR

T, °C	c_p, kJ/kg · °C
–10	1.0038
0	1.0041
10	1.0045
20	1.0049
30	1.0054
40	1.0059
50	1.0065

The c_p of air can be assumed to be constant at 1.005 kJ/kg · °C in the temperature range –10 to 50°C with an error under 0.2%.

For water

h_g = 2500.9 kJ/kg at 0°C

$c_{p,avg}$ = 1.82 kJ/kg · °C at –10 to 50°C range

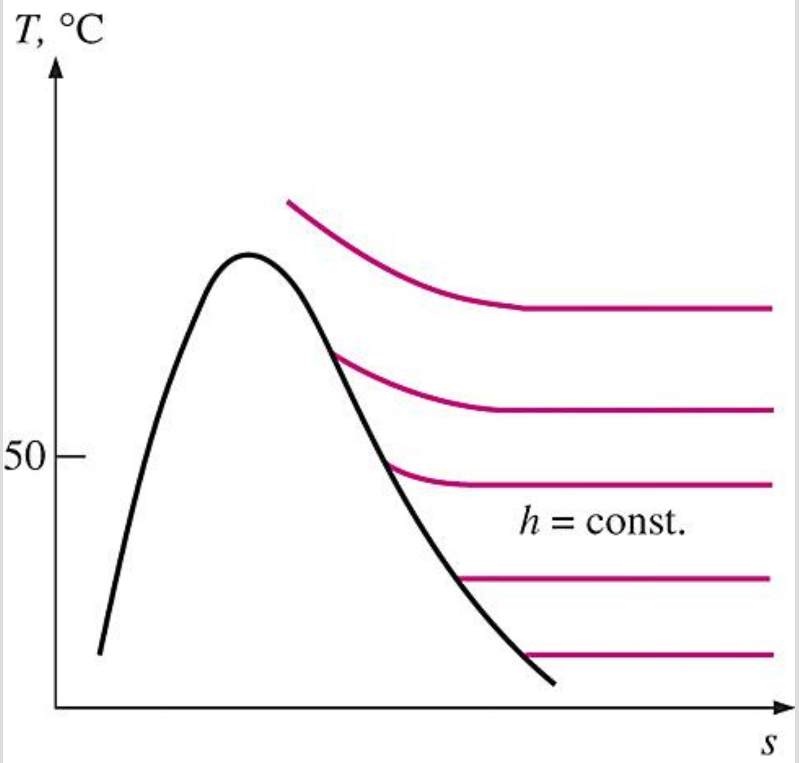
$$h_g(T) \cong 2500.9 + 1.82T \qquad \text{(kJ/kg)} \qquad T \text{ in °C}$$

$$h_g(T) \cong 1060.9 + 0.435T \qquad \text{(Btu/lbm)} \qquad T \text{ in °F}$$

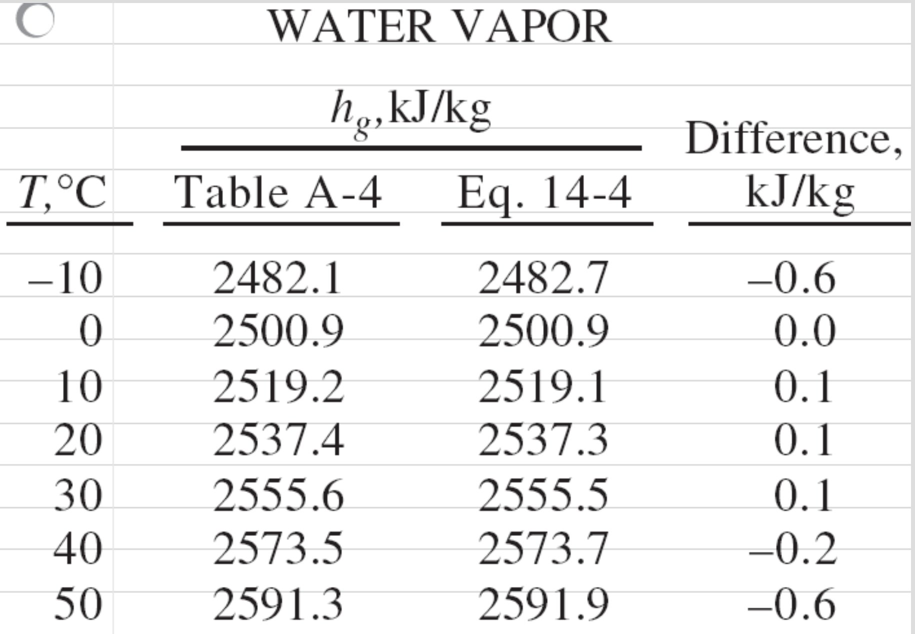
h = *h*(*T*) since water vapor is an ideal gas

$$h_v(T, \text{low } P) \cong h_g(T)$$

In the temperature range –10 to 50°C, the h_g of water can be determined from this equation with negligible error.



Below 50°C, the *h* = const. lines coincide with the *T* = const. lines in the superheated vapor region of water.



WATER VAPOR

T,°C	h_g, kJ/kg Table A-4	 Eq. 14-4	Difference, kJ/kg
–10	2482.1	2482.7	–0.6
0	2500.9	2500.9	0.0
10	2519.2	2519.1	0.1
20	2537.4	2537.3	0.1
30	2555.6	2555.5	0.1
40	2573.5	2573.7	–0.2
50	2591.3	2591.9	–0.6

SPECIFIC AND RELATIVE HUMIDITY OF AIR

Absolute or **specific humidity** (*humidity ratio*): The mass of water vapor present in a unit mass of dry air.

$$\omega = \frac{m_v}{m_a} \qquad \text{(kg water vapor/kg dry air)}$$

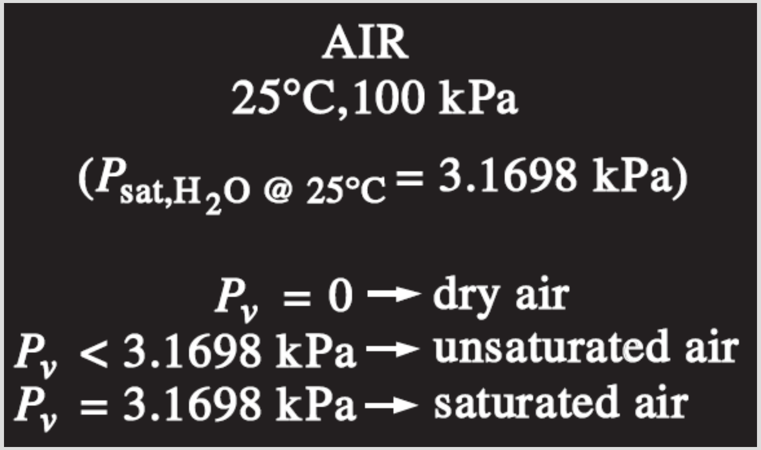
$$\omega = \frac{m_v}{m_a} = \frac{P_v V/R_v T}{P_a V/R_a T} = \frac{P_v/R_v}{P_a/R_a} = 0.622\frac{P_v}{P_a}$$

$$\omega = \frac{0.622P_v}{P - P_v} \qquad \text{(kg water vapor/kg dry air)}$$

Saturated air: The air saturated with moisture.

Relative humidity: The ratio of the amount of moisture the air holds (m_v) to the maximum amount of moisture the air can hold at the same temperature (m_g).

$$\phi = \frac{m_v}{m_g} = \frac{P_v V/R_v T}{P_g V/R_v T} = \frac{P_v}{P_g} \qquad P_g = P_{\text{sat @ }T}$$



AIR

25°C, 100 kPa

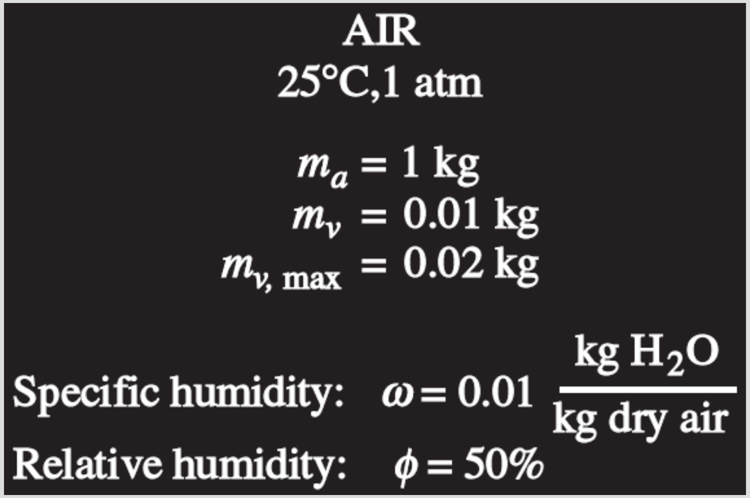
$(P_{\text{sat,H}_2\text{O @ 25°C}} = 3.1698 \text{ kPa})$

$P_v = 0 \rightarrow$ dry air

$P_v < 3.1698 \text{ kPa} \rightarrow$ unsaturated air

$P_v = 3.1698 \text{ kPa} \rightarrow$ saturated air

For saturated air, the vapor pressure is equal to the saturation pressure of water.



AIR

25°C, 1 atm

$m_a = 1 \text{ kg}$

$m_v = 0.01 \text{ kg}$

$m_{v,\max} = 0.02 \text{ kg}$

Specific humidity: $\omega = 0.01 \dfrac{\text{kg H}_2\text{O}}{\text{kg dry air}}$

Relative humidity: $\phi = 50\%$

The difference between specific and relative humidities.

$$\phi = \frac{\omega P}{(0.622 + \omega)P_g} \quad \text{and} \quad \omega = \frac{0.622\phi P_g}{P - \phi P_g}$$

What is the relative humidity of dry air and saturated air?

In most practical applications, the amount of dry air in the air–water-vapor mixture remains constant, but the amount of water vapor changes.

Therefore, the enthalpy of atmospheric air is expressed *per unit mass of dry air.*

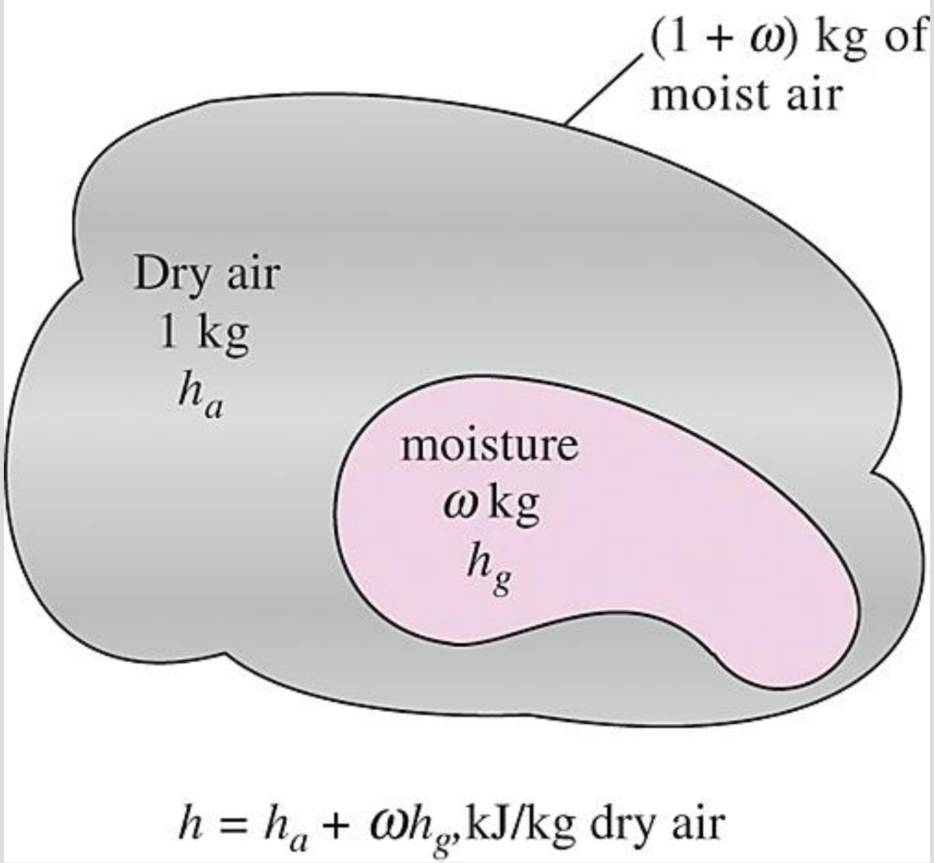
$$H = H_a + H_v = m_a h_a + m_v h_v$$

$$h = \frac{H}{m_a} = h_a + \frac{m_v}{m_a} h_v = h_a + \omega h_v$$

$$h_v \cong h_g$$

$$h = h_a + \omega h_g \qquad (\text{kJ/kg dry air})$$

Dry-bulb temperature:
The ordinary temperature of atmospheric air.

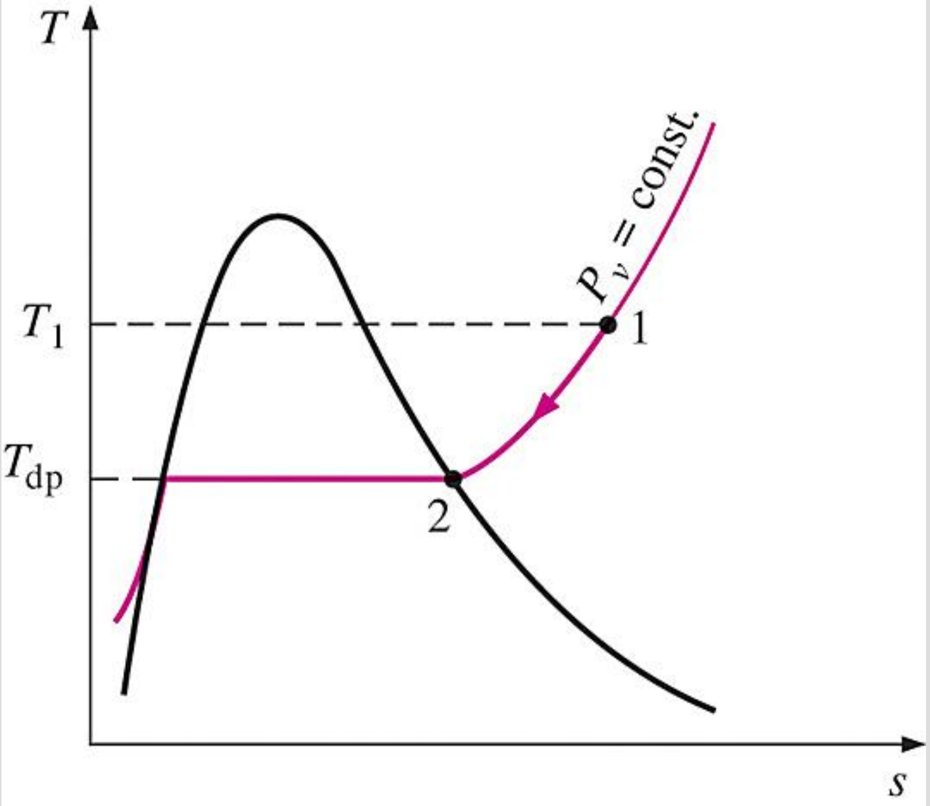


The enthalpy of moist (atmospheric) air is expressed per unit mass of dry air, not per unit mass of moist air.

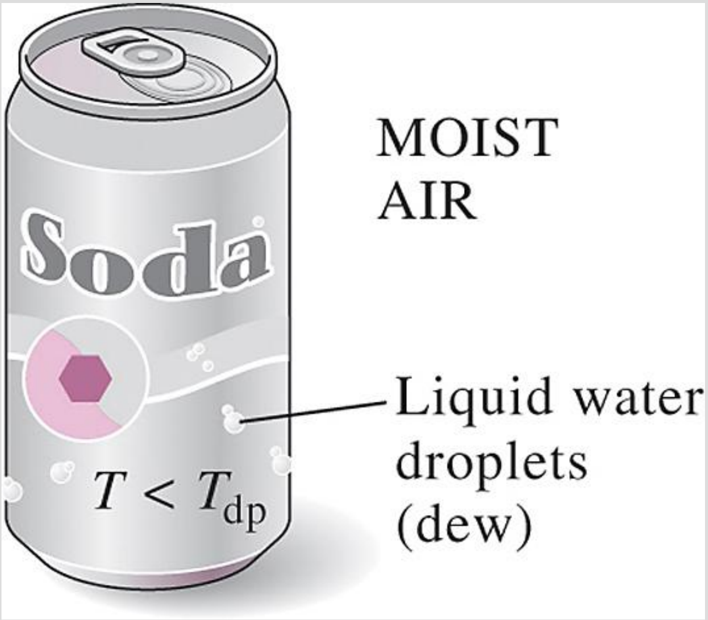
DEW-POINT TEMPERATURE

Dew-point temperature T_{dp}:
The temperature at which condensation begins when the air is cooled at constant pressure *(i.e.,* the saturation temperature of water corresponding to the vapor pressure.)

$$T_{dp} = T_{sat\ @\ P_v}$$



Constant-presssure cooling of moist air and the dew-point temperature on the *T-s* diagram of water.



When the temperature of a cold drink is below the dew-point temperature of the surrounding air, it “sweats.”

ADIABATIC SATURATION AND WET-BULB TEMPERATURES

$\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$ (The mass flow rate of dry air remains constant)

$\dot{m}_{w_1} + \dot{m}_f = \dot{m}_{w_2}$ (The mass flow rate of vapor in the air increases by an amount equal to the rate of evaporation $\dot{m}_f$)

$$\dot{m}_a\omega_1 + \dot{m}_f = \dot{m}_a\omega_2 \longrightarrow \dot{m}_f = \dot{m}_a(\omega_2 - \omega_1)$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

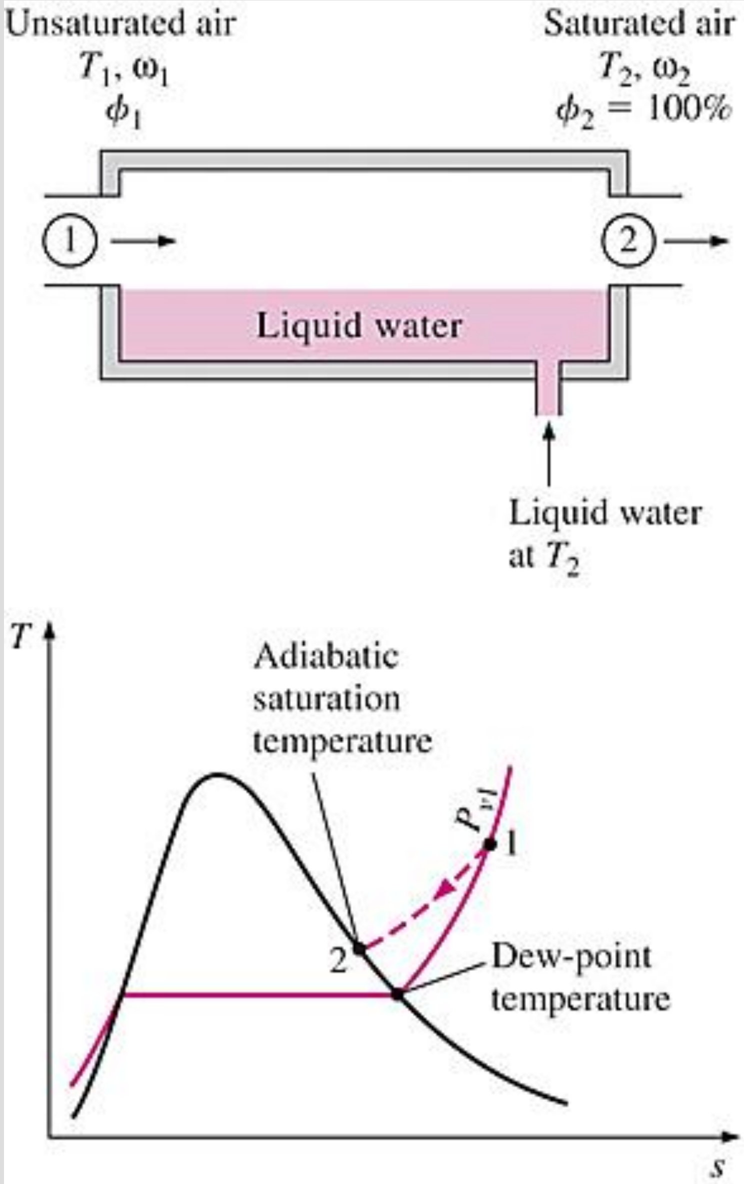
$$\dot{m}_a h_1 + \dot{m}_f h_{f_2} = \dot{m}_a h_2 \longrightarrow \dot{m}_a h_1 + \dot{m}_a(\omega_2 - \omega_1)h_{f_2} = \dot{m}_a h_2$$

$$h_1 + (\omega_2 - \omega_1)h_{f_2} = h_2$$

$$(c_p T_1 + \omega_1 h_{g_1}) + (\omega_2 - \omega_1)h_{f_2} = (c_p T_2 + \omega_2 h_{g_2})$$

$$\omega_1 = \frac{c_p(T_2 - T_1) + \omega_2 h_{fg_2}}{h_{g_1} - h_{f_2}} \qquad \omega_2 = \frac{0.622 P_{g_2}}{P_2 - P_{g_2}}$$

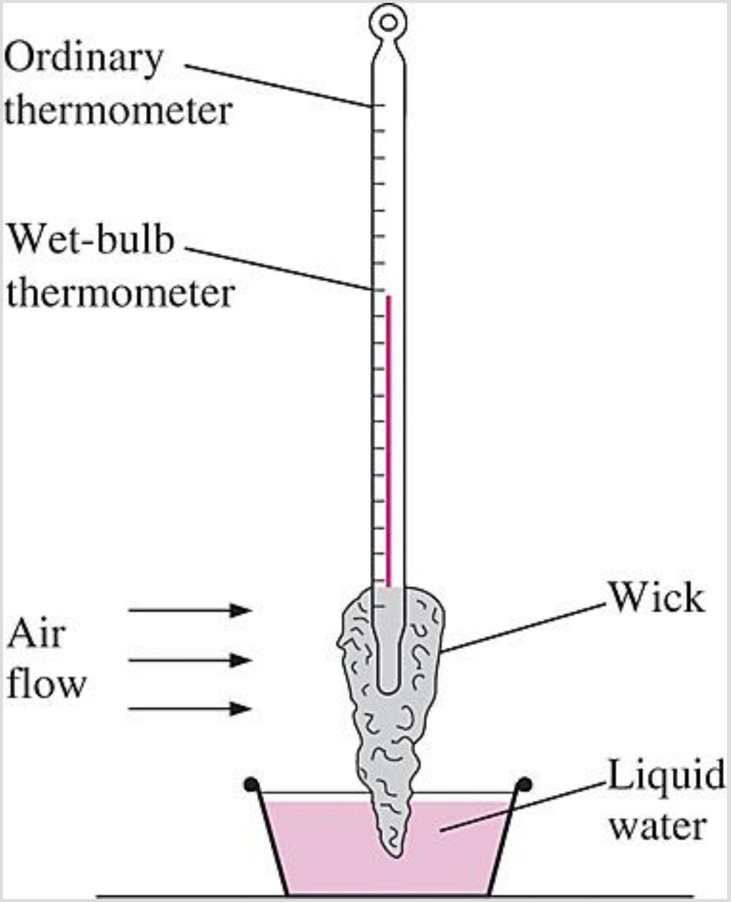
The specific humidity (and relative humidity) of air can be determined from these equations by measuring the pressure and temperature of air at the inlet and the exit of an adiabatic saturator.



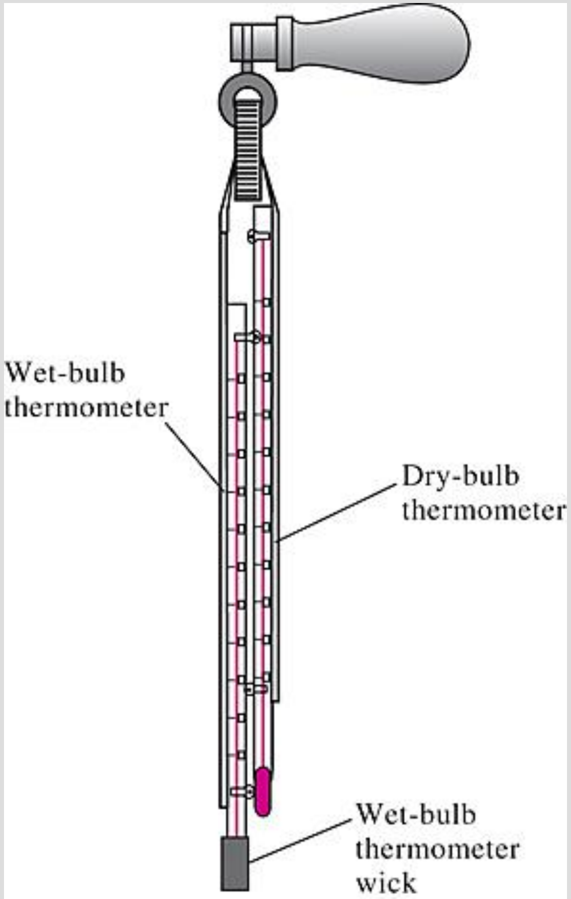
The adiabatic saturation process and its representation on a *T-s* diagram of water.

The adiabatic saturation process is not practical. To determine the absolute and relative humidity of air, a more practical approach is to use a thermometer whose bulb is covered with a cotton wick saturated with water and to blow air over the wick.

The temperature measured is the **wet-bulb temperature T_{wb}** and it is commonly used in A-C applications.



A simple arrangement to measure the wet-bulb temperature.

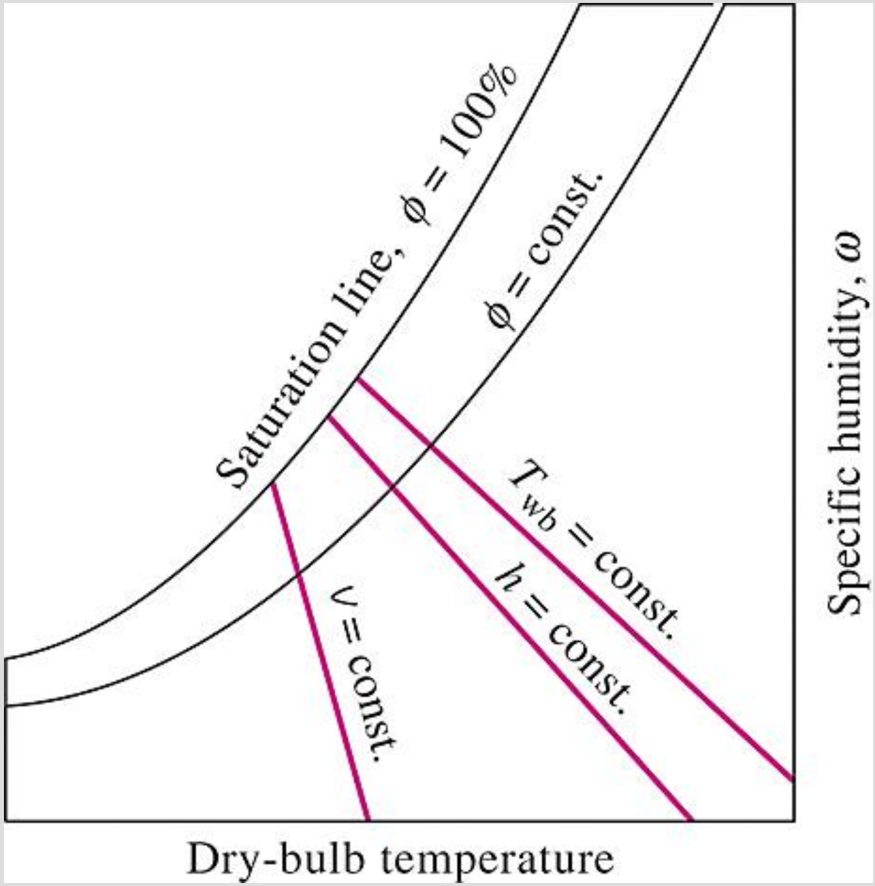


Sling psychrometer

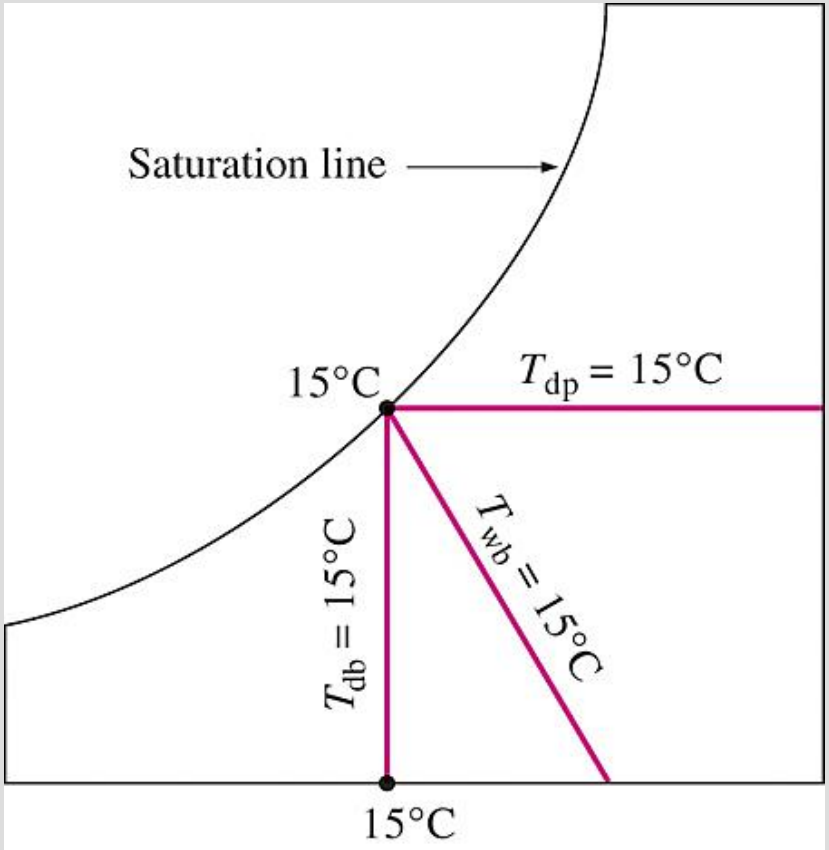
For air–water vapor mixtures at atmospheric pressure, T_{wb} is approximately equal to the adiabatic saturation temperature.

THE PSYCHROMETRIC CHART

Psychrometric charts: Present moist air properties in a convenient form. They are used extensively in A-C applications. The psychrometric chart serves as a valuable aid in visualizing the A-C processes such as heating, cooling, and humidification.



Schematic for a psychrometric chart.



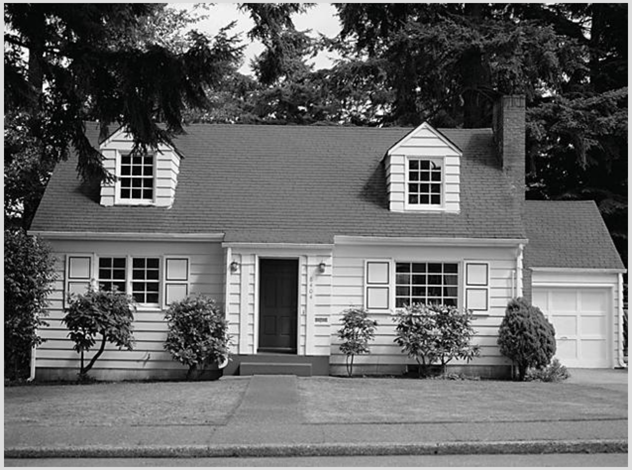
For saturated air, the dry-bulb, wet-bulb, and dew-point temperatures are identical.

HUMAN COMFORT AND AIR-CONDITIONING

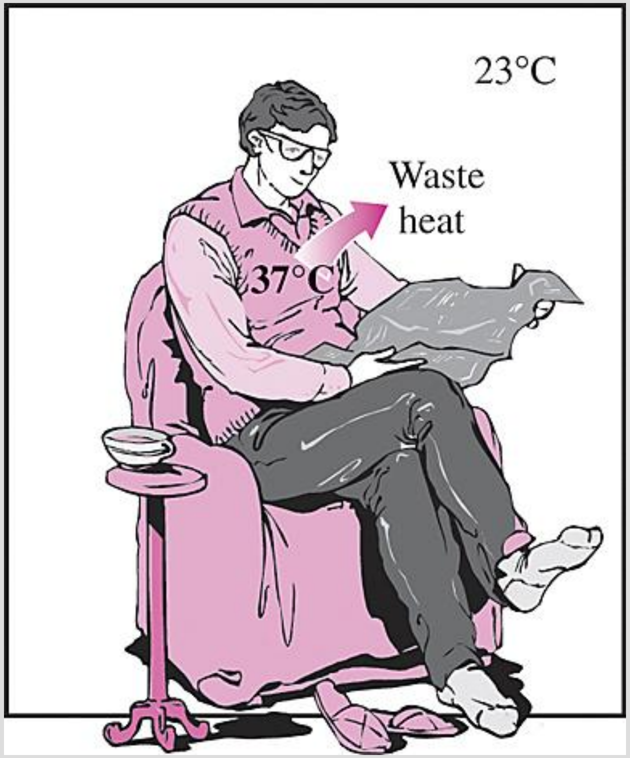
Today, modern air-conditioning systems can heat, cool, humidify, dehumidify, clean, and even deodorize the air–in other words, *condition* the air to peoples' desires.

The rate of heat generation by human body depends on the level of the activity. For an average adult male, it is about 87 W when sleeping, 115 W when resting or doing office work, and 440 W when doing heavy physical work.

When doing light work or walking slowly, about half of the rejected body heat is dissipated through perspiration as *latent heat* while the other half is dissipated through convection and radiation as *sensible heat*.

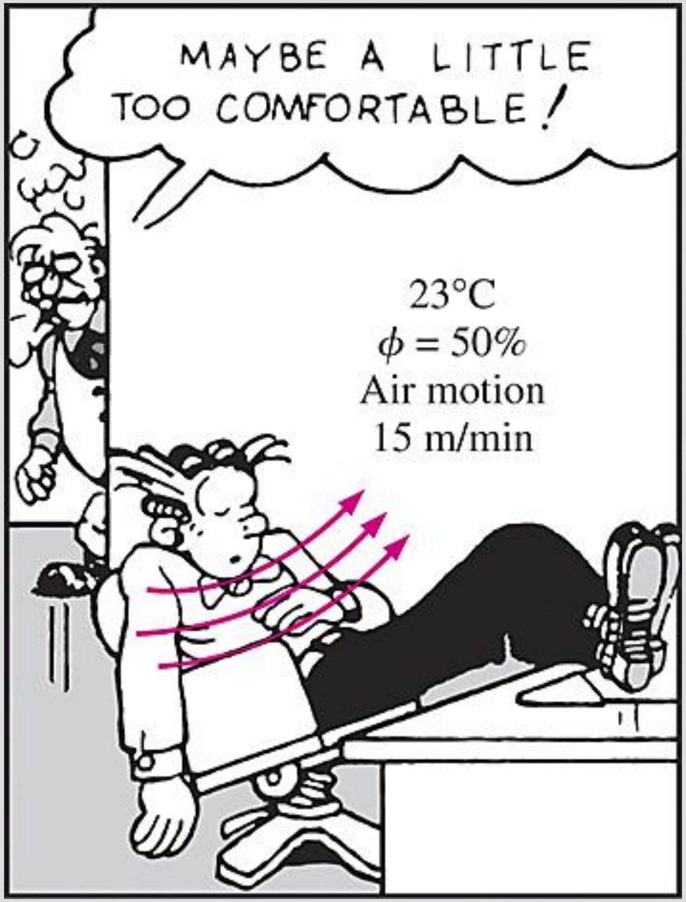


We cannot change the weather, but we can change the climate in a confined space by air-conditioning.



A body feels comfortable when it can freely dissipate its waste heat, and no more.

In an environment at 10°C with 48 km/h winds feels as cold as an environment at -7°C with 3 km/h winds as a result of the body-chilling effect of the air motion (the ***wind-chill factor***).



A comfortable environment.

The comfort of the human body depends primarily on three factors: **the (dry-bulb) temperature, relative humidity,** and **air motion**.

The relative humidity affects the amount of heat a body can dissipate through evaporation. Most people prefer a relative humidity of 40 to 60%.

Air motion removes the warm, moist air that builds up around the body and replaces it with fresh air. Air motion should be strong enough to remove heat and moisture from the vicinity of the body, but gentle enough to be unnoticed.

An important factor that affects human comfort is heat transfer by radiation between the body and the surrounding surfaces such as walls and windows.

Other factors that affect comfort are air cleanliness, odor, and noise.

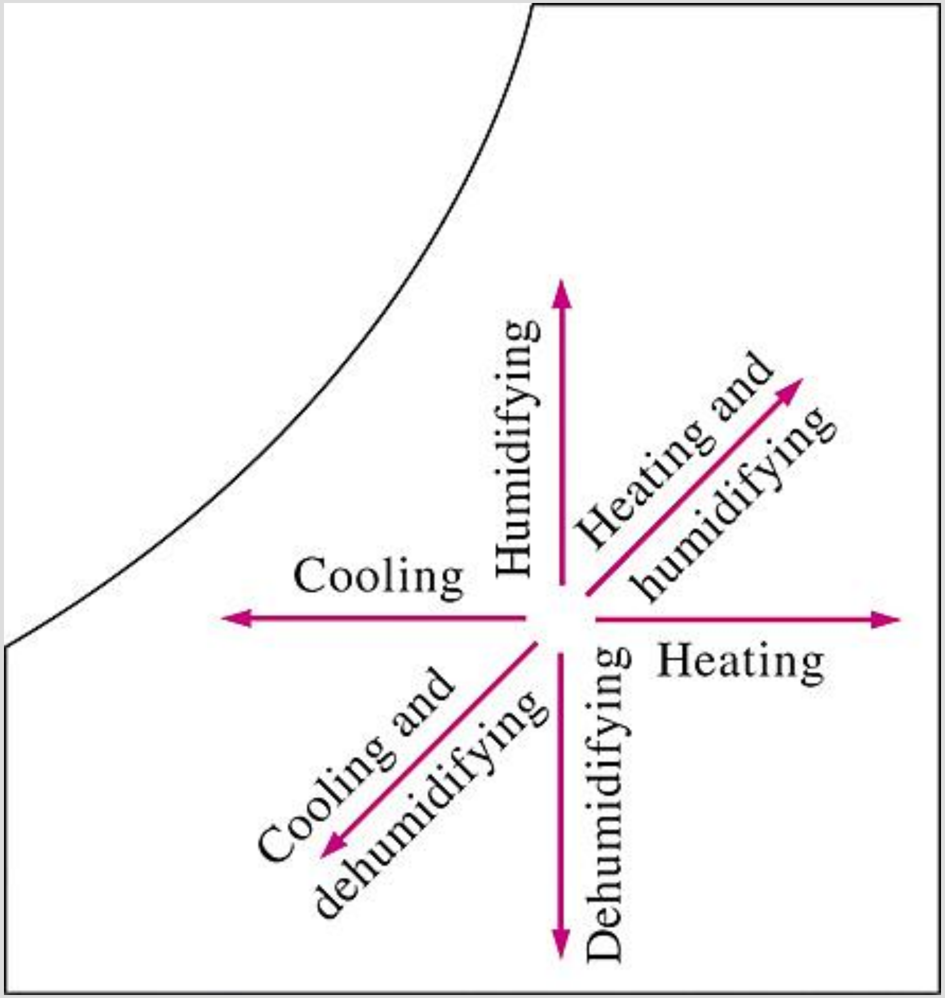
AIR-CONDITIONING PROCESSES

Maintaining a living space or an industrial facility at the desired temperature and humidity requires some processes called air-conditioning processes.

These processes include *simple heating* (raising the temperature), *simple cooling* (lowering the temperature), *humidifying* (adding moisture), and *dehumidifying* (removing moisture).

Sometimes two or more of these processes are needed to bring the air to a desired temperature and humidity level.

Air is commonly heated and humidified in winter and cooled and dehumidified in summer.



Various air-conditioning processes.

Most air-conditioning processes can be modeled as steady-flow processes with the following general mass and energy balances:

Mass balance $\dot{m}_{\text{in}} = \dot{m}_{\text{out}}$

Mass balance for dry air: $$\sum_{\text{in}} \dot{m}_a = \sum_{\text{out}} \dot{m}_a \qquad (\text{kg/s})$$

Mass balance for water: $$\sum_{\text{in}} \dot{m}_w = \sum_{\text{out}} \dot{m}_w \quad \text{or} \quad \sum_{\text{in}} \dot{m}_a \, \omega = \sum_{\text{out}} \dot{m}_a \, \omega$$

Energy balance $\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m} h = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \dot{m} h$$

The work term usually consists of the *fan work input*, which is small relative to the other terms in the energy balance relation.

Simple Heating and Cooling (ω = constant)

Many residential heating systems consist of a stove, a heat pump, or an electric resistance heater. The air in these systems is heated by circulating it through a duct that contains the tubing for the hot gases or the electric resistance wires.

Cooling can be accomplished by passing the air over some coils through which a refrigerant or chilled water flows.

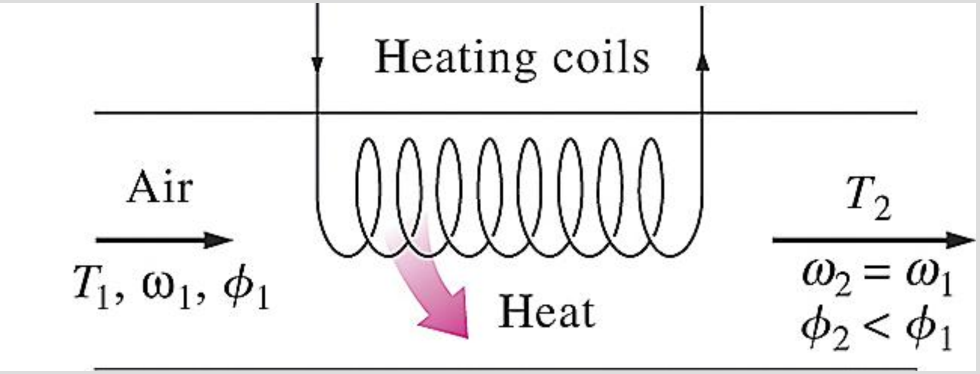
Heating and cooling appear as a horizontal line since no moisture is added to or removed from the air.

Dry air mass balance $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}a$

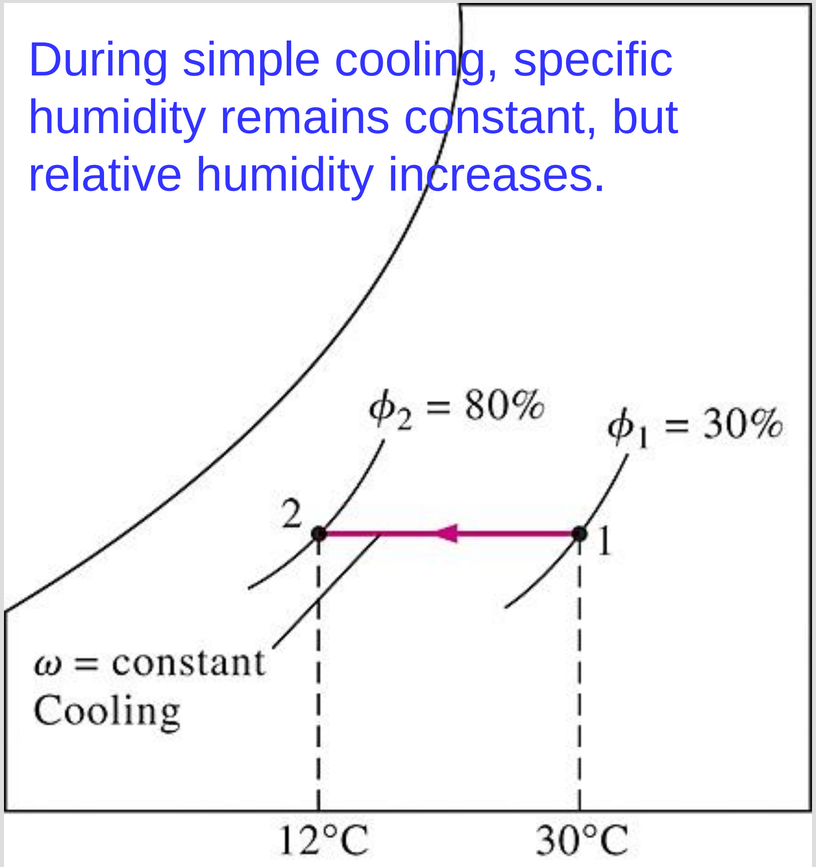
Water mass balance $\omega_1 = \omega_2$

Energy balance

$$\dot{Q} = \dot{m}_a(h_2 - h_1) \quad \text{or} \quad q = h_2 - h_1$$



During simple heating, specific humidity remains constant, but relative humidity decreases.


During simple cooling, specific humidity remains constant, but relative humidity increases.

Heating with Humidification

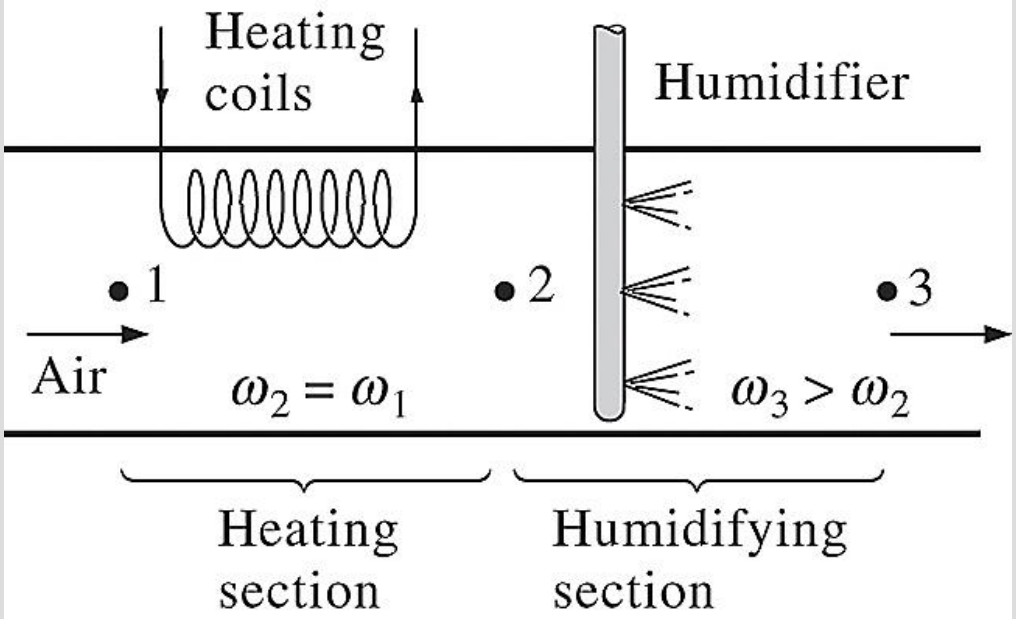
Problems with the low relative humidity resulting from simple heating can be eliminated by humidifying the heated air. This is accomplished by passing the air first through a heating section and then through a humidifying section.

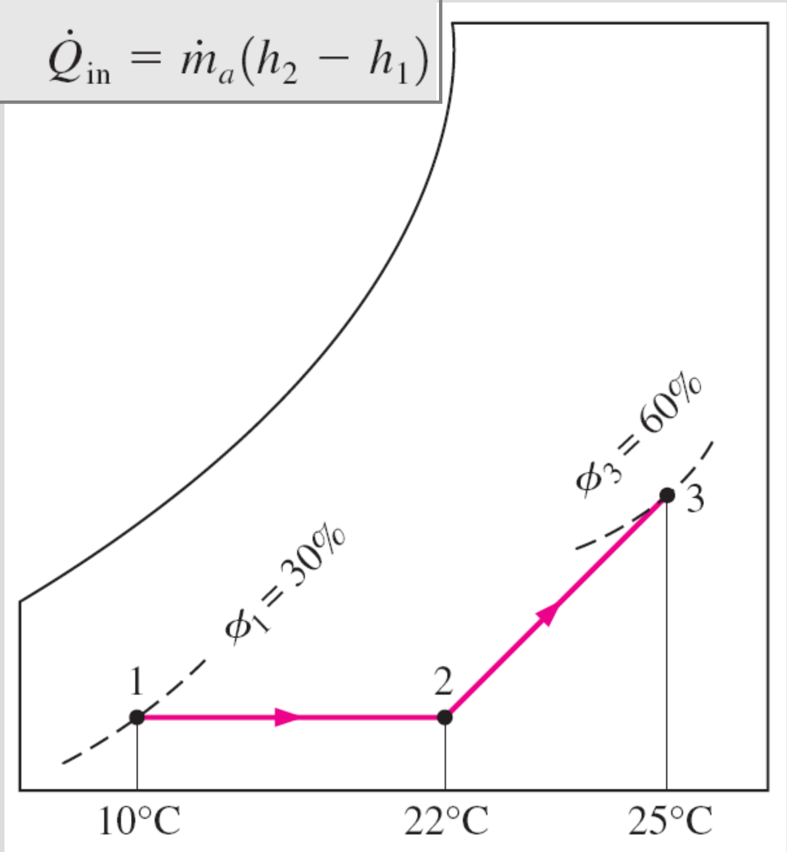
Dry air mass balance: $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$

Water mass balance: $\dot{m}_{a_1}\omega_1 = \dot{m}_{a_2}\omega_2 \rightarrow \omega_1 = \omega_2$

Energy balance: $\dot{Q}_{\text{in}} + \dot{m}_a h_1 = \dot{m}_a h_2 \rightarrow \dot{Q}_{\text{in}} = \dot{m}_a(h_2 - h_1)$

$$\boxed{\dot{m}_{a_2}\omega_2 + \dot{m}_w = \dot{m}_{a_3}\omega_3} \longrightarrow \boxed{\dot{m}_w = \dot{m}_a(\omega_3 - \omega_2)}$$





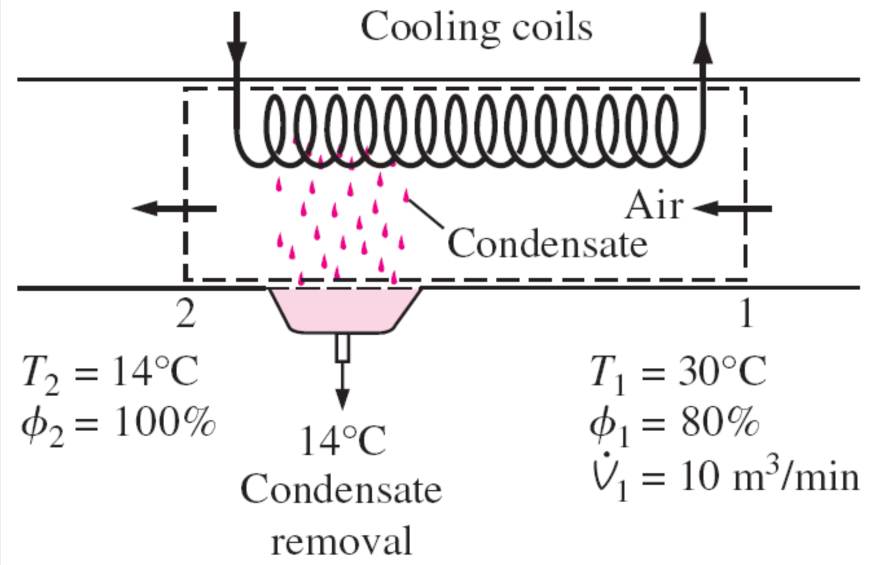
Cooling with Dehumidification

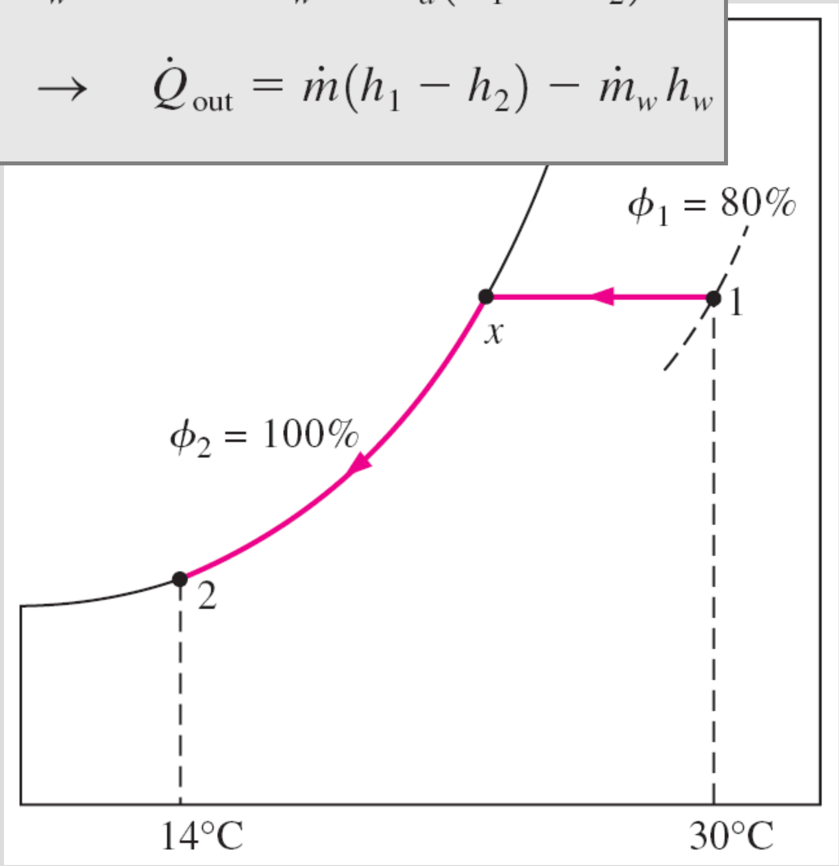
The specific humidity of air remains constant during a simple cooling process, but its relative humidity increases. If the relative humidity reaches undesirably high levels, it may be necessary to remove some moisture from the air, that is, to dehumidify it. This requires cooling the air below its dew-point temperature.

Dry air mass balance: $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$

Water mass balance: $\dot{m}_{a_1}\omega_1 = \dot{m}_{a_2}\omega_2 + \dot{m}_w \rightarrow \dot{m}_w = \dot{m}_a(\omega_1 - \omega_2)$

Energy balance: $\sum_{\text{in}} \dot{m}h = \dot{Q}_{\text{out}} + \sum_{\text{out}} \dot{m}h \rightarrow \dot{Q}_{\text{out}} = \dot{m}(h_1 - h_2) - \dot{m}_w h_w$

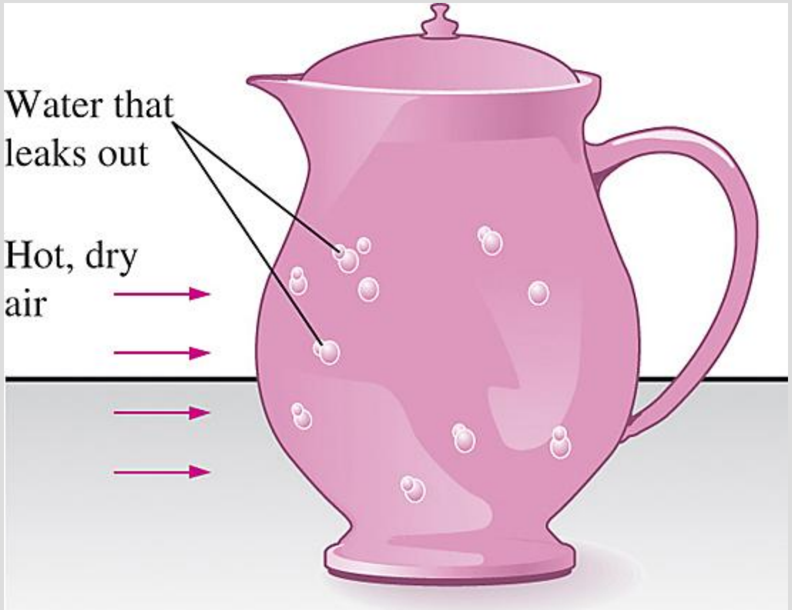




Evaporative Cooling

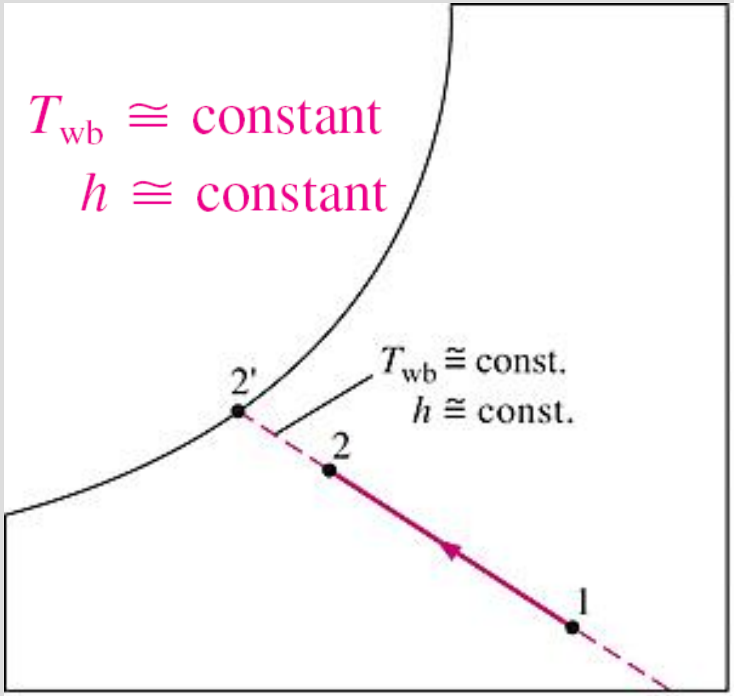
In desert (*hot and dry*) climates, we can avoid the high cost of conventional cooling by using *evaporative coolers*, also known as *swamp coolers*.

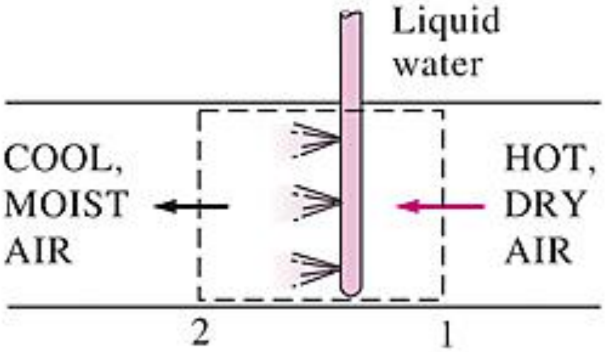
As water evaporates, the latent heat of vaporization is absorbed from the water body and the surrounding air. As a result, both the water and the air are cooled during the process.



Water in a porous jug left in an open, breezy area cools as a result of evaporative cooling.

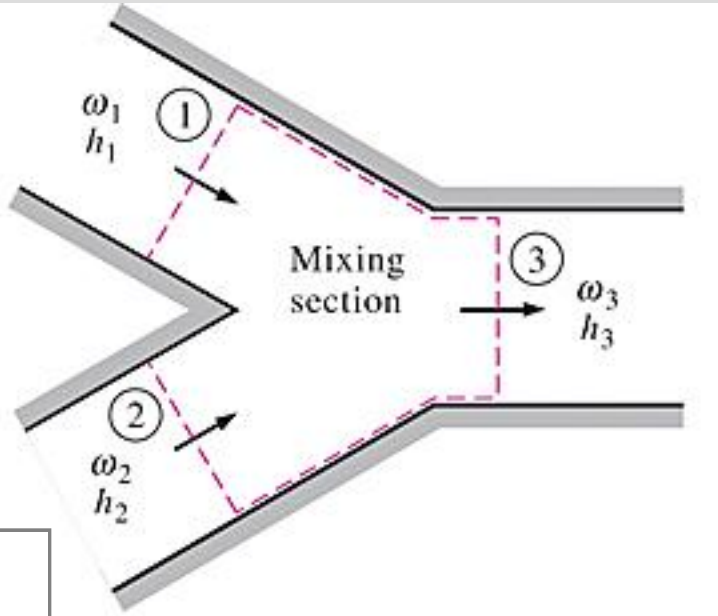
This process is essentially identical to adiabatic saturation process.





Adiabatic Mixing of Airstreams

Many A-C applications require the mixing of two airstreams. This is particularly true for large buildings, most production and process plants, and hospitals, which require that the conditioned air be mixed with a certain fraction of fresh outside air before it is routed into the living space.



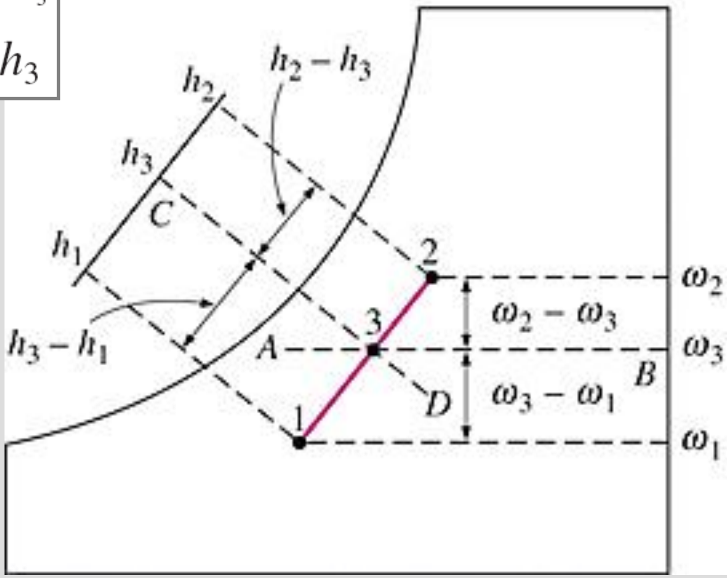
Mass of dry air: $\dot{m}_{a_1} + \dot{m}_{a_2} = \dot{m}_{a_3}$

Mass of water vapor: $\omega_1\dot{m}_{a_1} + \omega_2\dot{m}_{a_2} = \omega_3\dot{m}_{a_3}$

Energy: $\dot{m}_{a_1}h_1 + \dot{m}_{a_2}h_2 = \dot{m}_{a_3}h_3$

$$\frac{\dot{m}_{a_1}}{\dot{m}_{a_2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

When two airstreams at states 1 and 2 are mixed adiabatically, the state of the mixture lies on the straight line connecting the two states.



Wet Cooling Towers

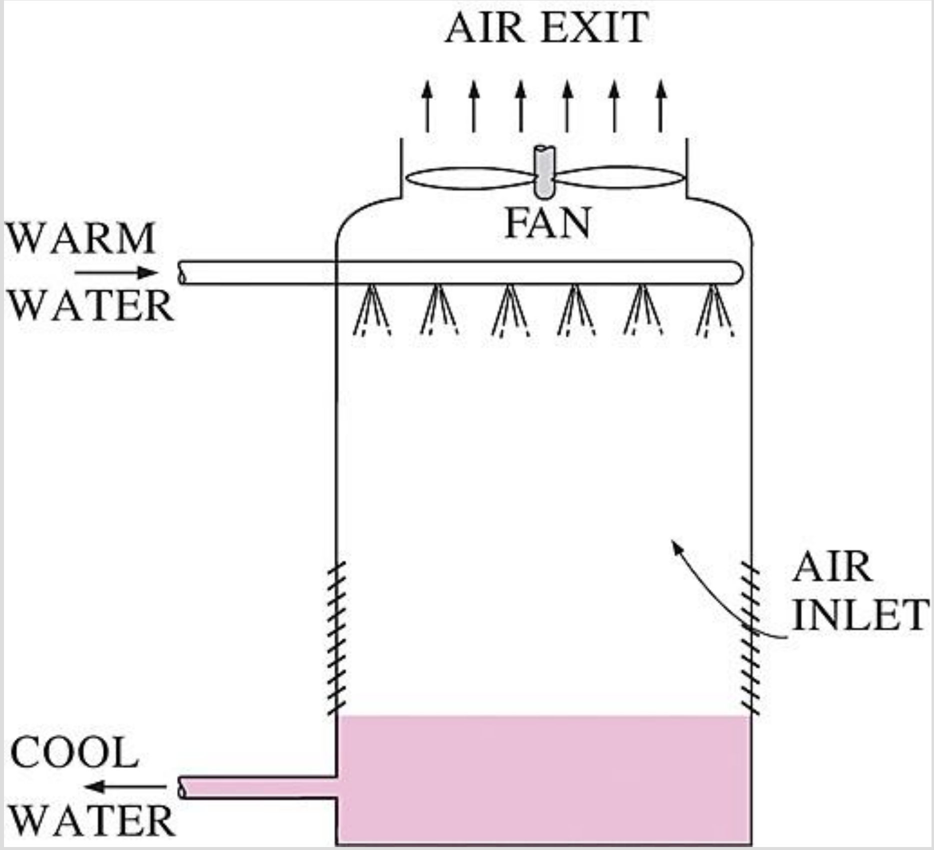
Power plants, large air-conditioning systems, and some industries generate large quantities of waste heat that is often rejected to cooling water from nearby lakes or rivers.

In some cases, however, the cooling water supply is limited or thermal pollution is a serious concern.

In such cases, the waste heat must be rejected to the atmosphere, with cooling water recirculating and serving as a transport medium for heat transfer between the source and the sink (the atmosphere).

One way of achieving this is through the use of wet cooling towers.

A **wet cooling tower** is essentially a semi-enclosed evaporative cooler.

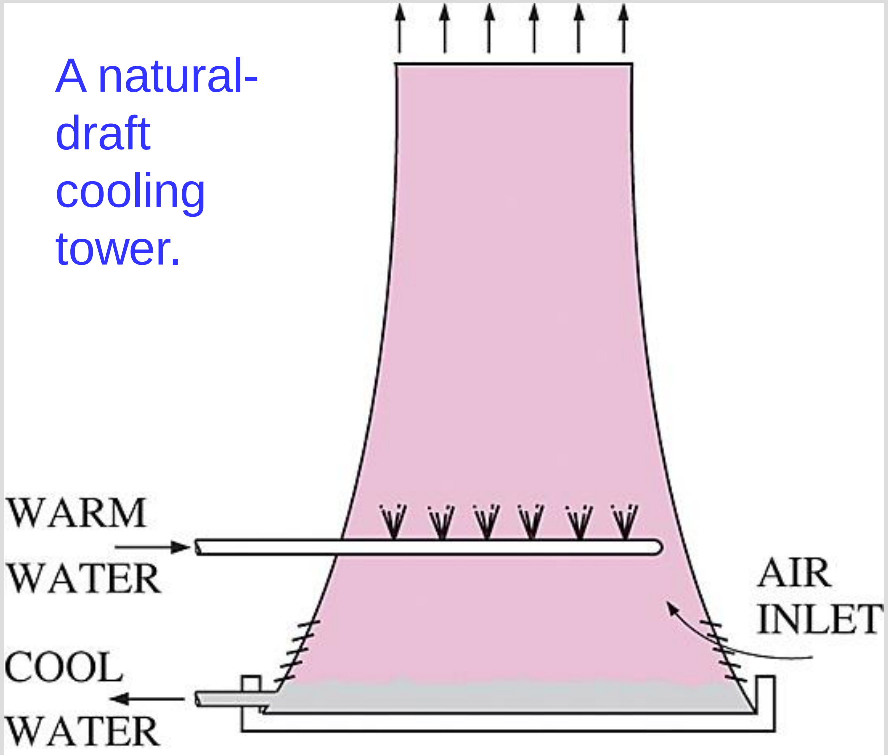


An induced-draft counterflow cooling tower.

Natural-draft cooling tower: It looks like a large chimney and works like an ordinary chimney. The air in the tower has a high water-vapor content, and thus it is lighter than the outside air. Consequently, the light air in the tower rises, and the heavier outside air fills the vacant space, creating an airflow from the bottom of the tower to the top.

Spray pond: The warm water is sprayed into the air and is cooled by the air as it falls into the pond,

Cooling pond: Dumping the waste heat into a still pond, which is basically a large artificial lake open to the atmosphere.



A natural-draft cooling tower.

A spray pond.

Summary

- Dry and atmospheric air
- Specific and relative humidity of air
- Dew-point temperature
- Adiabatic saturation and wet-bulb temperatures
- The psychrometric chart
- Human comfort and air-conditioning
- Air-conditioning processes
    - ✓ Simple heating and cooling
    - ✓ Heating with humidification
    - ✓ Cooling with dehumidification
    - ✓ Evaporative cooling
    - ✓ Adiabatic mixing of airstreams
    - ✓ Wet cooling towers