Chapter 13:

GAS-VAPOR MIXTURES AND AIR-CONDITIONING

HUMAN COMFORT AND AIR-CONDITIONING

Human beings want to live in an environment that is neither hot nor cold, neither humid nor dry.

The human body can be viewed as a heat engine whose energy input is food.

As with any other heat engine, the human body generates waste heat that must be rejected to the environment.

For an average adult male, it is about 87 W when sleeping, 115 W when resting or doing office work, 230 W when bowling, and 440 W when doing heavy physical work.

The corresponding numbers for an adult female are about 15 percent less.

A body will feel comfortable in environments in which it can dissipate this waste heat comfortably.

HUMAN COMFORT AND AIR-CONDITIONING

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

Most people feel comfortable when the environment temperature is between 22 and 27°C (72 and 80°F).

Relative humidity is a measure of air's ability to absorb more moisture.

High relative humidity slows down heat rejection by evaporation, and low relative humidity speeds it up.

Most people prefer a relative humidity of 40 to 60 percent.

Air motion improves heat rejection by removing the warm, moist air that builds up around the body and replaces it with fresh air.

Most people feel comfortable at an airspeed of about 15 m/min.

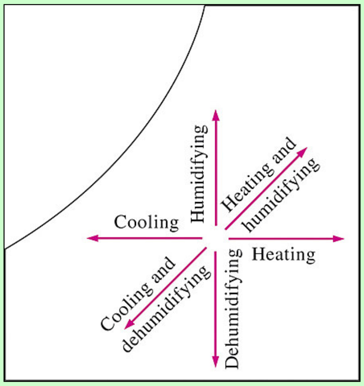
AIR-CONDITIONING PROCESSES

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.

Various air-conditioning processes are illustrated on the psychrometric chart.



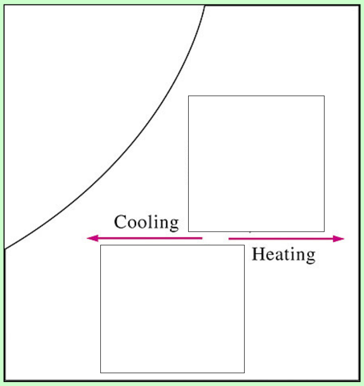
AIR-CONDITIONING PROCESSES

Notice that simple heating and cooling processes appear as horizontal lines on this chart since the moisture content of the air remains constant (ω = constant) during these processes.

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

Notice how these processes appear on the psychrometric chart.

Most air-conditioning processes can be modeled as steady-flow processes.



AIR-CONDITIONING PROCESSES

Most air-conditioning processes can be modeled as steady-flow processes, and thus the *mass balance* relation $m_{\text{in}} = m_{\text{out}}$ can be expressed for *dry air* and *water* as:

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

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

Disregarding the kinetic and potential energy changes, the *steady-flow energy balance* relation $E_{\text{in}} = E_{\text{out}}$ can be expressed in this case as:

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

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

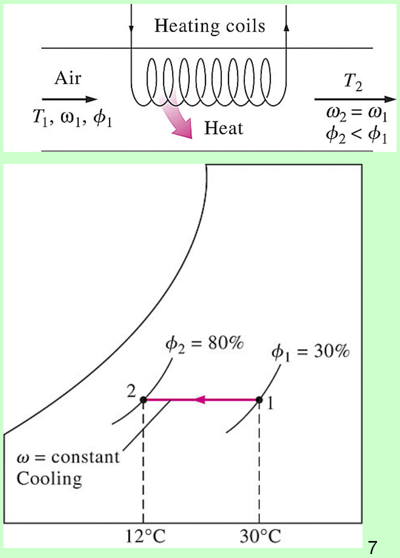
Next we examine some commonly encountered processes in air-conditioning.

Simple Heating and Cooling (ω = constant)

In many heating systems, the air is heated by circulating it through a duct that contains the tubing for the hot gases or the electric resistance wires, as shown.

The amount of moisture in the air remains constant during this process since no moisture is added to or removed from the air.

That is, the specific humidity of the air remains constant (ω = constant) during a heating (or cooling) process with no humidification or dehumidification.

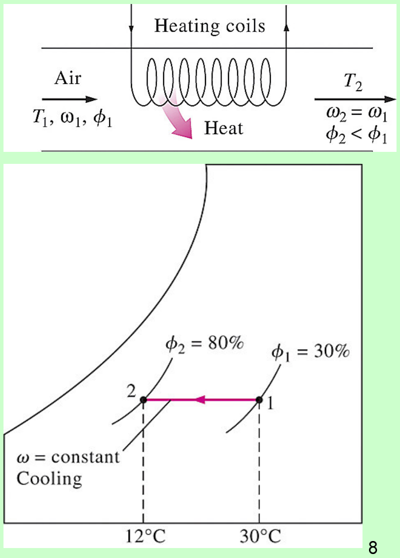


Simple Heating and Cooling (ω = constant)

Such a heating process proceeds in the direction of increasing dry-bulb temperature following a line of constant specific humidity on the psychrometric chart, which appears as a horizontal line.

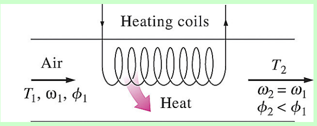
Notice that the relative humidity of air decreases during a heating process even if the specific humidity ω remains constant.

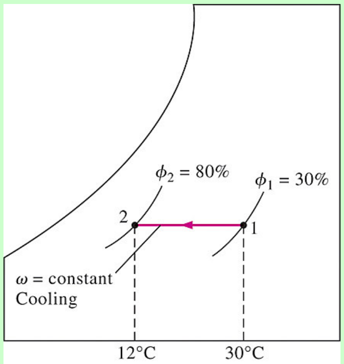
This is because the relative humidity is the ratio of the moisture content to the moisture capacity of air at the same temperature, and moisture capacity increases with temperature.



Simple Heating and Cooling (ω = constant)

A cooling process at constant specific humidity is similar to the heating process discussed above, except the dry-bulb temperature decreases and the relative humidity increases during such a process, as shown.





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

The conservation of mass equations for a heating or cooling process that involves no humidification or dehumidification reduce to $m_{a1} = m_{a2}$ for dry air and $\omega_1 = \omega_2$ for water.

The conservation of energy equation in this case reduces to:

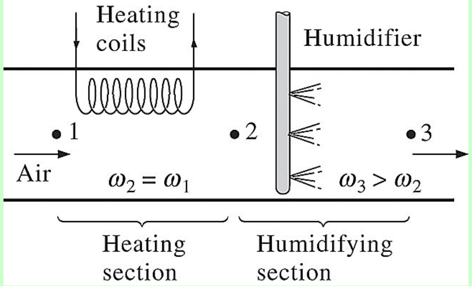
$$\dot{Q} = \dot{m}_a(h_2 - h_1) \quad \text{or} \quad q = h_2 - h_1$$

Heating with Humidification

Problems associated 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 (process 1-2) and then through a humidifying section (process 2-3), as shown.

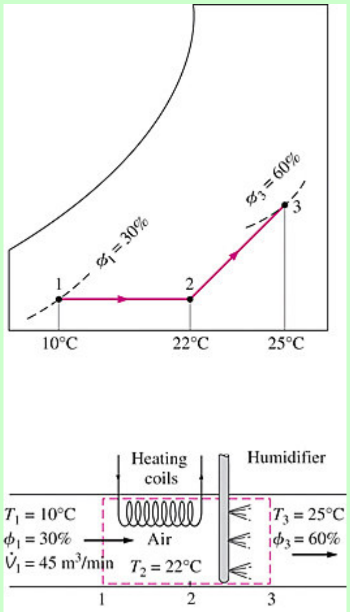
The location of state 3 depends on how the humidification is accomplished.



If steam is introduced in the humidification section, this will result in humidification with additional heating ($T_3 > T_2$).

If humidification is accomplished by spraying water into the airstream instead, which results in the cooling of the heated airstream ($T_3 < T_2$).

Example 13-5
Heating and Humidification of Air

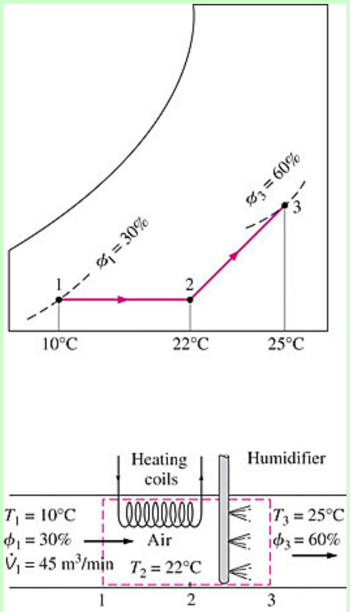


An air-conditioning system is to take in outdoor air at 10°C and 30 percent relative humidity at a steady rate of 45 m^3/min and to condition it to 25°C and 60 percent relative humidity. The outdoor air is first heated to 22°C in the heating section and then humidified by the injection of hot steam in the humidifying section. Assuming the entire process takes place at a pressure of 100 kPa, determine:

(*a*) the rate of heat supply in the heating section and

(*b*) the mass flow rate of the steam required in the humidifying section.

Example 13-5
Heating and Humidification of Air



(*a*) the rate of heat supply in the heating section and

$$P_{v_1} = \phi_1 P_{g_1} = \phi P_{\text{sat @ }10°C} = (0.3)(1.2281\ \text{kPa}) = 0.368\ \text{kPa}$$

$$P_{a_1} = P_1 - P_{v_1} = (100 - 0.368)\ \text{kPa} = 99.632\ \text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_a} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283\ \text{K})}{99.632\ \text{kPa}} = 0.815\ \text{m}^3/\text{kg dry air}$$

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{45\ \text{m}^3/\text{min}}{0.815\ \text{m}^3/\text{kg}} = 55.2\ \text{kg/min}$$

$$\omega_1 = \frac{0.622 P_{v_1}}{P_1 - P_{v_1}} = \frac{0.622(0.368\ \text{kPa})}{(100 - 0.368)\ \text{kPa}} = 0.0023\ \text{kg H}_2\text{O/kg dry air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g_1} = (1.005\ \text{kJ/kg}\cdot°\text{C})(10°\text{C}) + (0.0023)(2519.2\ \text{kJ/kg}) = 15.8\ \text{kJ/kg dry air}$$

$$h_2 = c_p T_2 + \omega_2 h_{g_2} = (1.005\ \text{kJ/kg}\cdot°\text{C})(22°\text{C}) + (0.0023)(2541.0\ \text{kJ/kg}) = 28.0\ \text{kJ/kg dry air}$$

$$\dot{Q}_{\text{in}} = \dot{m}_a(h_2 - h_1) = (55.2\ \text{kg/min})[(28.0 - 15.8)\ \text{kJ/kg}] = \mathbf{673\ kJ/min}$$

Example 13-5

Heating and Humidification of Air

(*b*) the mass flow rate of the steam required in the humidifying section.

$$\dot{m}_{a_2}\omega_2 + \dot{m}_w = \dot{m}_{a_3}\omega_3$$

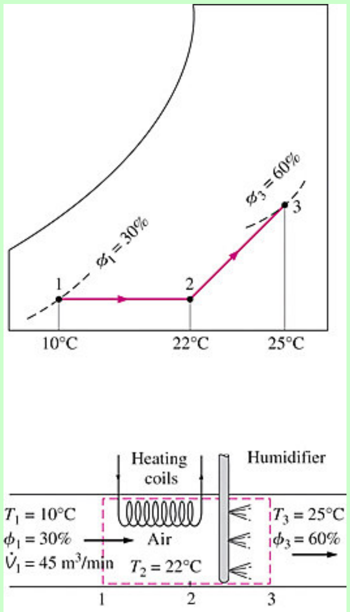
$$\dot{m}_w = \dot{m}_a(\omega_3 - \omega_2)$$

$$\omega_3 = \frac{0.622\phi_3 P_{g_3}}{P_3 - \phi_3 P_{g_3}} = \frac{0.622(0.60)(3.1698\text{ kPa})}{[100 - (0.60)(3.1698)]\text{ kPa}}$$

$$= 0.01206\text{ kg H}_2\text{O/kg dry air}$$

$$\dot{m}_w = (55.2\text{ kg/min})(0.01206 - 0.0023)$$

$$= \mathbf{0.539\text{ kg/min}}$$



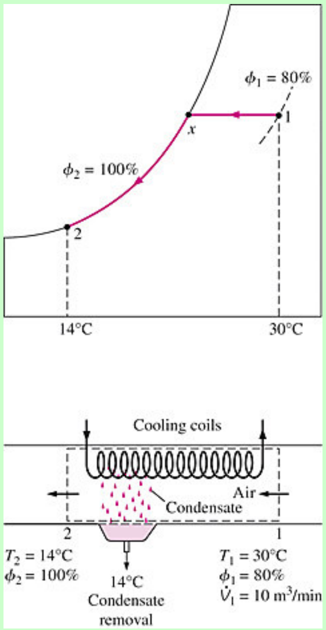
Cooling with Dehumidification

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.

The cooling process with dehumidifying is illustrated schematically and on the psychrometric chart in conjunction with Example 13–6.



Cooling with Dehumidification

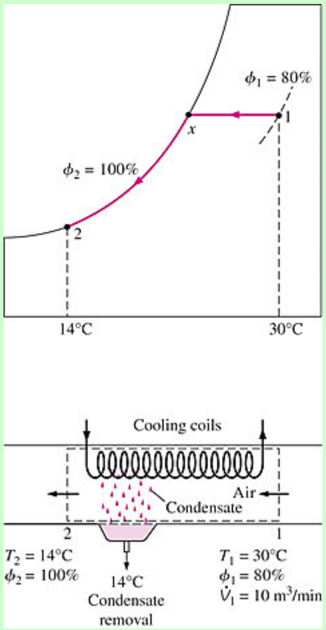
Hot, moist air enters the cooling section at state 1.

As it passes through the cooling coils, its temperature decreases and its relative humidity increases at constant specific humidity.

If the cooling section is sufficiently long, air reaches its dew point (state *x*, saturated air).

Further cooling of air results in the condensation of part of the moisture in the air.

Air remains saturated during the entire condensation process, which follows a line of 100 percent relative humidity until the final state (state 2) is reached.



Cooling with Dehumidification

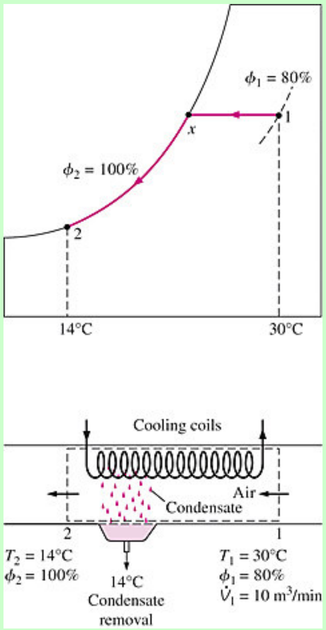
The water vapor that condenses out of the air during this process is removed from the cooling section through a separate channel.

The condensate is usually assumed to leave the cooling section at T_2.

The cool, saturated air at state 2 is usually routed directly to the room, where it mixes with the room air.

In some cases, however, the air at state 2 may be at the right specific humidity but at a very low temperature.

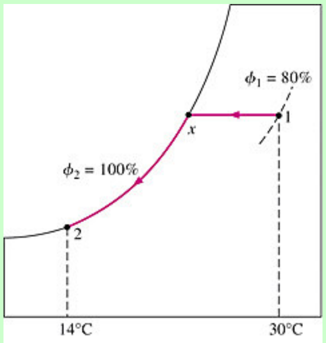
In such cases, air is passed through a heating section where its temperature is raised to a more comfortable level before it is routed to the room.

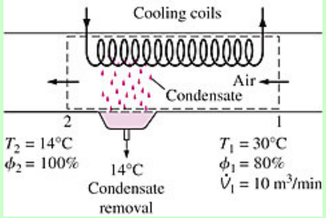


Example 13-6

Cooling and Dehumidification of Air

Air enters a window air conditioner at 1 atm, 30°C, and 80 percent relative humidity at a rate of 10 m³/min, and it leaves as saturated air at 14°C. Part of the moisture in the air that condenses during the process is also removed at 14°C. Determine the rates of heat and moisture removal from the air.





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

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

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

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{10\ \text{m}^3/\text{min}}{0.889\ \text{m}^3/\text{kg dry air}} = 11.25\ \text{kg/min}$$

$$\dot{m}_w = (11.25\ \text{kg/min})(0.0216 - 0.0100) = \mathbf{0.131\ kg/min}$$

$$\dot{Q}_{out} = (11.25\ \text{kg/min})[(85.4 - 39.3)\ \text{kJ/kg}] - (0.131\ \text{kg/min})(58.8\ \text{kJ/kg})$$
$$= \mathbf{511\ kJ/min}$$

Evaporative Cooling

Conventional cooling systems operate on a refrigeration cycle, and they can be used in any part of the world.

But they have a high initial and operating cost.

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

You have probably noticed that on a hot, dry day the air feels a lot cooler when the yard is watered.

This is because water absorbs heat from the air as it evaporates.

Evaporative Cooling

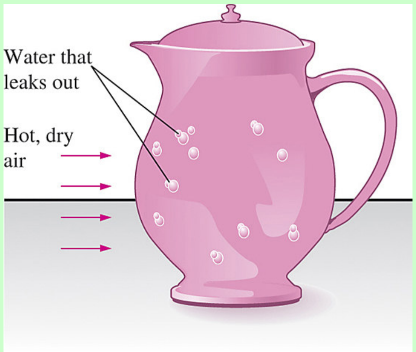
Evaporative cooling is based on a simple principle: As water evaporates, the latent heat of vaporization is absorbed from the water body and the surrounding air.

As a result, both the water and the air are cooled during the process. This approach has been used for thousands of years to cool water.

A porous jug or pitcher filled with water is left in an open, shaded area.

A small amount of water leaks out through the porous holes, and the pitcher "sweats."

In a dry environment, this water evaporates and cools the remaining water in the pitcher as shown.



Evaporative Cooling

An evaporative cooler works on the same principle.

The evaporative cooling process is shown schematically and on a psychrometric chart.

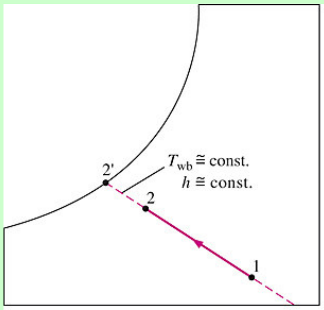
Hot, dry air at state 1 enters the evaporative cooler, where it is sprayed with liquid water.

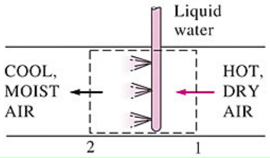
Part of the water evaporates during this process by absorbing heat from the airstream.

As a result, the temperature of the airstream decreases and its humidity increases (state 2).

In the limiting case, the air leaves the evaporative cooler saturated at state 2'.

This is the lowest temperature that can be achieved by this process.





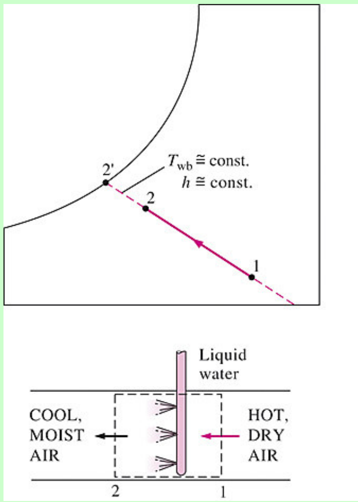
Evaporative Cooling

The evaporative cooling process follows a line of constant wet-bulb temperature on the psychrometric chart.

$$T_{wb} \cong \text{constant}$$

Since the constant-wetbulb- temperature lines almost coincide with the constant-enthalpy lines, the enthalpy of the airstream can also be assumed to remain constant. That is,

$$h \cong \text{constant}$$



Example 13-7

Evaporative Cooling of Air by a Swamp Cooler

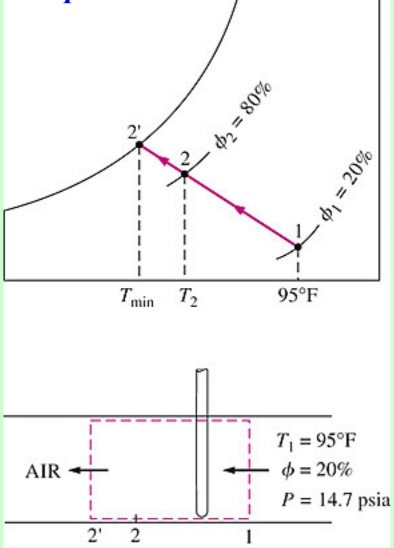
Air enters an evaporative (or swamp) cooler at 14.7 psi, 95°F, and 20 percent relative humidity, and it exits at 80 percent relative humidity. Determine:

(*a*) the exit temperature of the air and

(*b*) the lowest temperature to which the air can be cooled by this evaporative cooler.

$$T_2 = 70.4°\text{F}$$

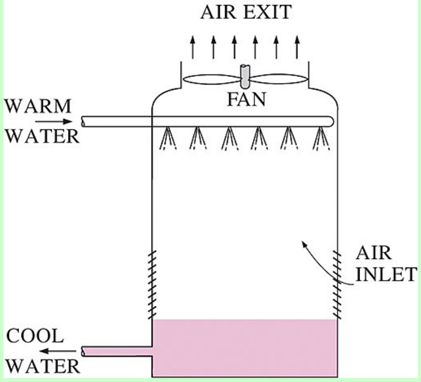
$$T_{min} = T_{2'} = 66.0°\text{F}$$



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).

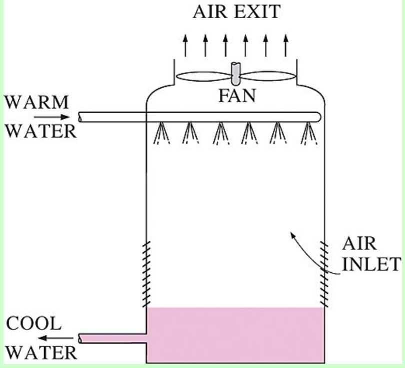
One way of achieving this is through the use of wet cooling towers.

Wet Cooling Towers

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

An induced-draft counter-flow wet cooling tower is shown schematically.

Air is drawn into the tower from the bottom and leaves through the top.



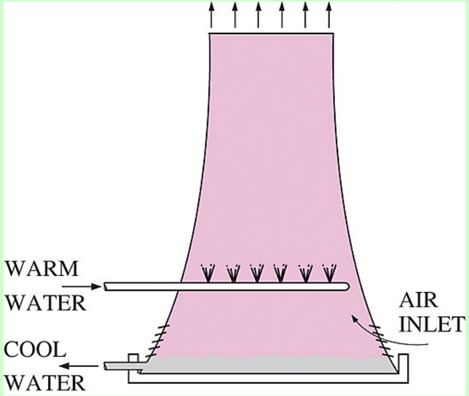
Warm water from the condenser is pumped to the top of the tower and is sprayed into this air-stream. The purpose of spraying is to expose a large surface area of water to the air. As the water droplets fall under the influence of gravity, a small fraction of water (usually a few percent) evaporates and cools the remaining water. The temperature and the moisture content of the air increase during this process. The cooled water collects at the bottom of the tower and is pumped back to the condenser to absorb additional waste heat.

Wet Cooling Towers

The air circulation in the cooling tower described is provided by a fan, and therefore it is classified as a forced-draft cooling tower.

Another popular type of cooling tower is the **natural-draft cooling tower,** which 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. The flow rate of air is controlled by the conditions of the atmospheric air.



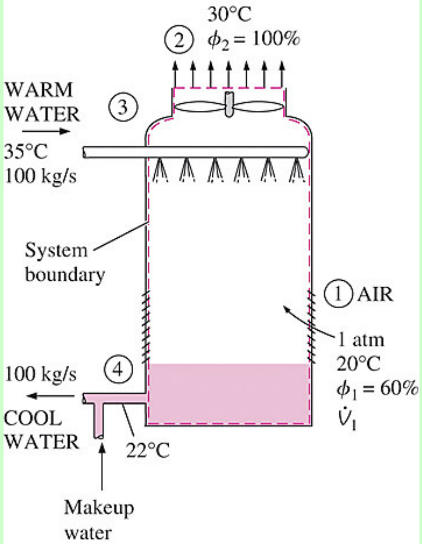
Example 13-9

Cooling of a Power Plant by a Cooling Tower

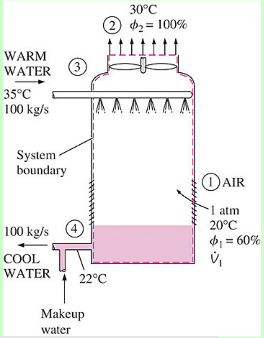
Cooling water leaves the condenser of a power plant and enters a wet cooling tower at 35°C at a rate of 100 kg/s. Water is cooled to 22°C in the cooling tower by air that enters the tower at 1 atm, 20°C, and 60 percent relative humidity and leaves saturated at 30°C. Neglecting the power input to the fan, determine:

(a) the volume flow rate of air into the cooling tower and

(*b*) the mass flow rate of the required makeup water.



Example 13-9
Cooling of a Power Plant by a Cooling Tower



Cooling water leaves the condenser of a power plant and enters a wet cooling tower at 35°C at a rate of 100 kg/s. Water is cooled to 22°C in the cooling tower by air that enters the tower at 1 atm, 20°C, and 60 percent relative humidity and leaves saturated at 30°C. Neglecting the power input to the fan, determine (*a*) the volume flow rate of air into the cooling tower and (*b*) the mass flow rate of the required makeup water.

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

Water mass balance: $\dot{m}_3 + \dot{m}_{a_1}\omega_1 = \dot{m}_4 + \dot{m}_{a_2}\omega_2$

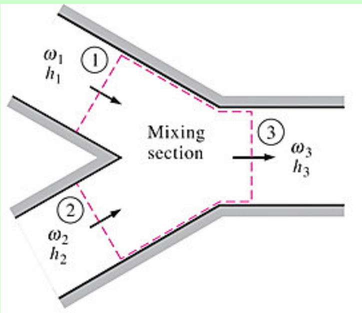
or $\dot{m}_3 - \dot{m}_4 = \dot{m}_a(\omega_2 - \omega_1) = \dot{m}_{\text{makeup}}$

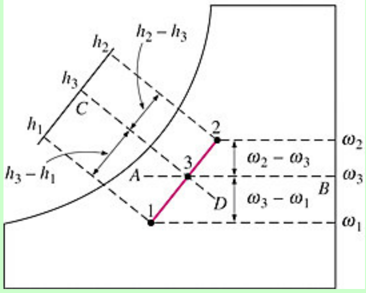
Energy balance: $\sum_{\text{in}} \dot{m}h = \sum_{\text{out}} \dot{m}h \rightarrow \dot{m}_{a_1}h_1 + \dot{m}_3h_3 = \dot{m}_{a_2}h_2 + \dot{m}_4h_4$

or

$$\dot{m}_3h_3 = \dot{m}_a(h_2 - h_1) + (\dot{m}_3 - \dot{m}_{\text{makeup}})h_4$$

Adiabatic Mixing of Airstreams





Many air-conditioning 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.

The mixing is accomplished by simply merging the two airstreams, as shown.

Adiabatic Mixing of Airstreams

The the mass and energy balances for the adiabatic mixing of two airstreams reduce to:

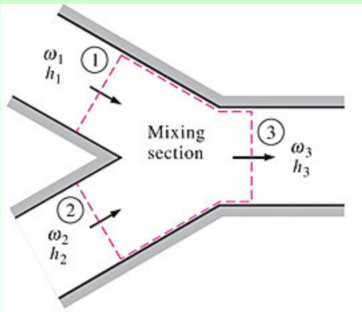
Mass of dry air: $\dot{m}_{a_1} + \dot{m}_{a_2} = \dot{m}_{a_3}$

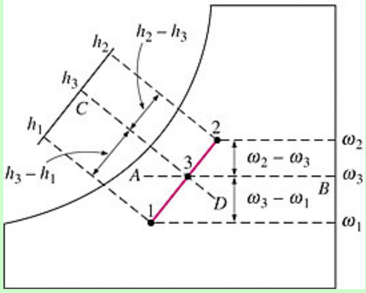
Mass of water vapor: $\omega_1\dot{m}_{a_1} + \omega_2\dot{m}_{a_2} = \omega_3\dot{m}_{a_3}$

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

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

Thus we conclude that *when two airstreams at two different states (states 1 and 2) are mixed adiabatically, the state of the mixture (state 3) lies on the straight line connecting states 1 and 2 on the psychrometric chart, and the ratio of the distances 2-3 and 3-1 is equal to the ratio of mass flow rates* m_{a1}*and* m_{a2}.





Example 13-8
Mixing of Conditioned Air with Outdoor Air

Saturated air leaving the cooling section of an air-conditioning system at 14°C at a rate of 50 m^3/min is mixed adiabatically with the outside air at 32°C and 60 percent relative humidity at a rate of 20 m^3/min. Assuming that the mixing process occurs at a pressure of 1 atm, determine the specific humidity, the relative humidity, the dry-bulb temperature, and the volume flow rate of the mixture.

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

$$\frac{60.5}{22.5} = \frac{0.0182 - \omega_3}{\omega_3 - 0.010} = \frac{79.0 - h_3}{h_3 - 39.4}$$

ω_3 = **0.0122 kg H$_2$O/kg dry air**

$h_3 = 50.1$ kJ/kg dry air