



University of Hilla
Department of Refrigeration and Air Conditioning
Technologies

Fundamental of Air Conditioning and Refrigeration
Part 2

Compiled by

Mr. Ali Hussein Ghalta

Assist. Lecturer in Department of Refrigeration and Air Conditioning
Technologies

Email: Alihussein@hilla-unc.edu.iq

2.1 Sensible Heating of Air:

Sensible heat will be added to the moist air while passing it over the hot dry surface. Normally, the heating surface is steam or hot water coil, whose surface temperature is above DBT of the air. As the air comes in contact with the warm surface, the DBT of air increases and tends to approach the temperature of the heating surface.

Since no moisture is added or removed from the air the specific humidity remains constant. The process is illustrated with a schematic diagram as in Figure 2.1. The process takes place along the constant DPT line. For steady flow conditions, the required rate of heat addition is

$$Q_{1-3} = m_1(h_3 - h_1) \quad (2.1)$$

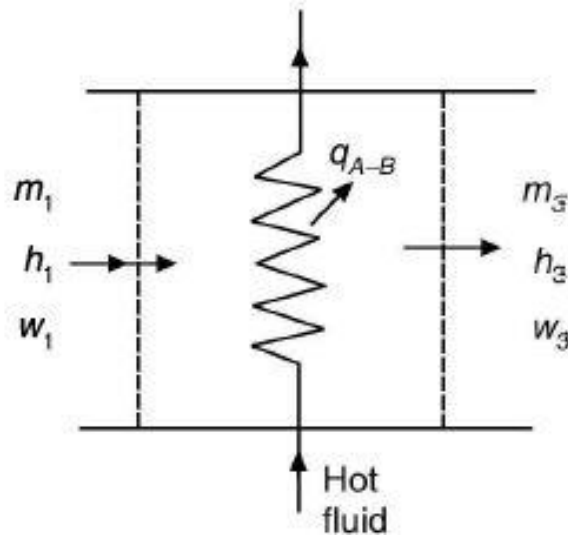


Figure 2.1 Heating of moist air by hot fluid coil

The process takes place along the constant moisture content line, here T_{db2} or T_2 is the heater temperature. Heat added per kg of dry air can also be found as

$$\begin{aligned} Q &= c_{pa}(T_{db3} - T_{db1}) + wc_{pv}(T_{db3} - T_{db1}) \\ &= (c_{pa} + wc_{pv})(T_{db3} - T_{db1}) \\ &= c_{pm}(T_{db3} - T_{db1}) \text{ KJ/Kg of dry air} \end{aligned} \quad (2.2)$$

Where c_{pm} is the specific heat of moist air.

Example 2.1 : Moist air, saturated at 10°C, flows over a heating coil at the rate of 5000 m³/h. Air leaves the coil at 40°C. Plot the process on a psychrometric chart determine the following:

- (a) WBT of air
- (b) The sensible heat transferred in KW
- (c) The total heat transferred in KW.

Solution: The point A is located on the saturation curve at 10°C (Fig. 2.2b).

$w_A = 7.7$ g/kg dry air and $h_A = 29.7$ KJ/kg dry air

$v_a = 0.812$ m³/kg dry air.

Locate state B. $h_B = 60.2$ KJ/Kg dry air, $w_B = w_A = 7.7$ g/kg dry air

(a) WBT at state A = 10°C

WBT at state B = 20.2°C

Mass flow rate of air

$$m_A = 5000 / (0.812 \times 3600) = 1.71 \text{ kg/s}$$

$$\begin{aligned} \text{(b) Sensible heat transfer rate} &= m_A \times (h_B - h_A) \\ &= (1.71)(60.2 - 29.7) \\ &= 52.17 \text{ kw} \end{aligned}$$

(c) In this example sensible heat is also equal to total heat, as there is no change in humidity ratio.

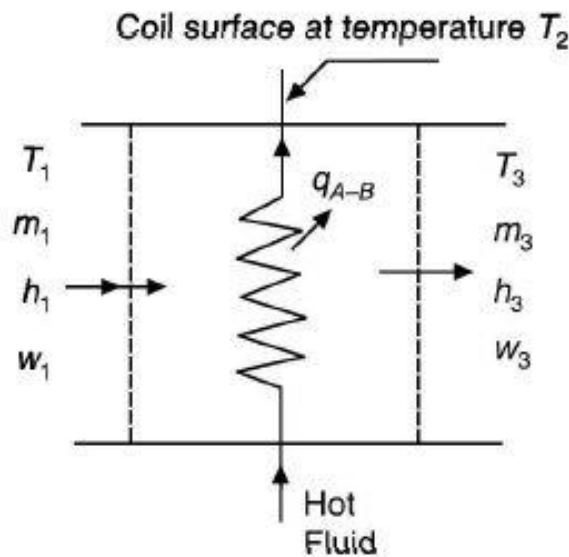


Figure. 2.2a Heating of air by hot fluid coil-Example 2.1

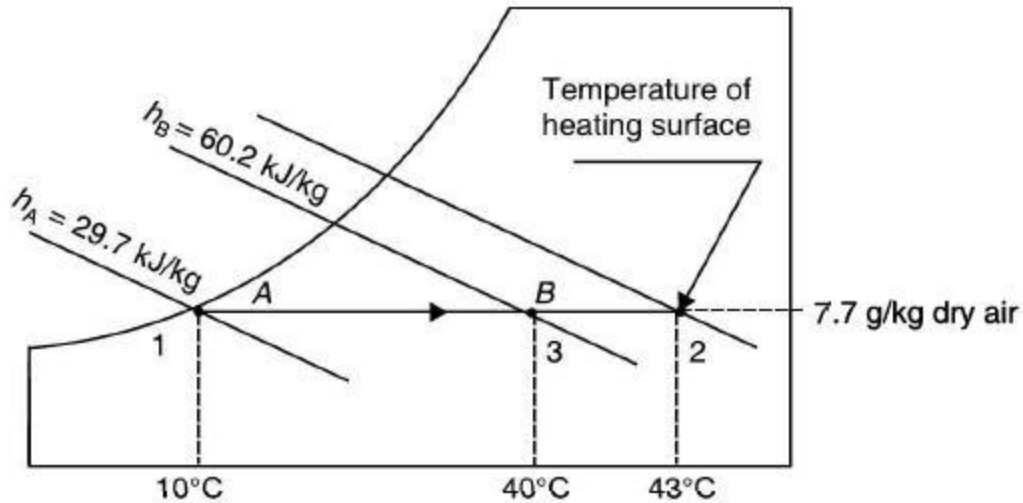


Figure. 2.2b Heating process on psychrometric chart-Example 2.1

Coil bypass factor: If all the air flowing over the coil comes into contact with the heating surface of the coil and remains in contact for a sufficiently long time, then the DBT of the air leaving the coil and the coil surface temperature will be same. However, practically air does not remain in contact with the heating surface for a long time and also some part of the air does not contact the surface. This means some air will bypass the coil. Therefore, the net effect is that the temperature of air at the outlet is less than the hot surface temperature. This is defined by a factor known as bypass factor. It is as indicated with respect to Figure 2.3.

The inability of coil to heat or cool the air to its temperature is indicated by a factor called Bypass Factor (BF).

$$BF = \frac{\text{Temperature drop that is not achieved}}{\text{Temperature drop that could be achieved}}$$

$$= \frac{T_2 - T_3}{T_2 - T_1} \quad (2.3)$$

Where

T_1 = DBT of air entering the coil

T_3 = DBT of air leaving the coil

T_2 = mean effective temperature of coil.

The bypass factor depends upon the following.

- (i) Number of rows of coil : Lesser is the number of rows, the higher is the BF, and greater the number of rows, the lesser is the BF. Coil are available from 2 rows to as high as 12 rows.
- (ii) Air velocity: For higher air velocity, BF is higher. The normal air velocity range is above 160m/min.

The bypass factors range from 0.01 to 0.15 as per the application.

Example 2.2: Calculate the bypass factor of the heating coil defined in Example 2.1, if its mean effective temperature of the coil surface is 43°C.
Solution: Using Eq. (2.3) the coil BF is

$$BF = \frac{43-40}{43-10} = 0.09$$

It means that 9% of the total air quantity passes through the heating coil without making contact with the coil surface.

2.2 Sensible Cooling of Moist Air:

Sensible cooling of moist air can be done by passing it over a cooling coil whose surface temperature is kept below the DBT of entering air and above the DP temperature. In this process, no moisture is added or removed, and DP temperature and latent heat content of air remain the same throughout the cooling process. Therefore, the process is represented as a horizontal line from right to left, depending upon the end conditions of air [Figure 2.3(a)]. The total change in heat (enthalpy) content is equal to the change in sensible heat.

Figure 2.3(b) shows the cooling process on psychrometric chart. The air can be cooled to surface temperature of coil. But this requires contact of air with coil surface for a sufficient period. The cooling of air depends on the number of rows of coil, depth of the coil and the velocity of air approaching the coil.

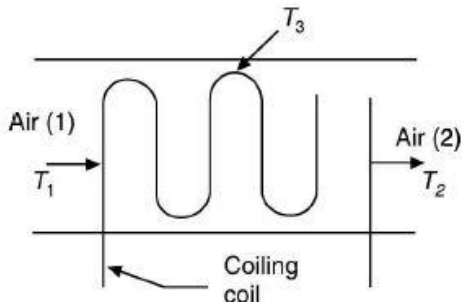


Figure 2.3(a) Sensible cooling

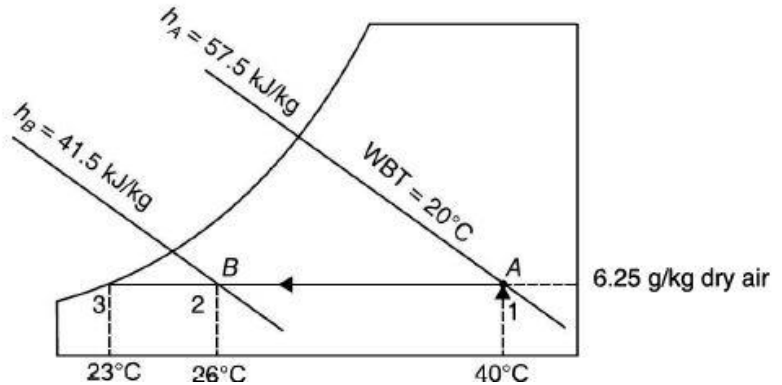


Figure 2.3(b) Sensible cooling on psychrometric chart

The heat transfer between the air and the cooling coil indicates that the temperature difference between the air and the coil surface is large at the beginning (first few rows of the coil). At subsequent rows this difference decreases. So, the last few rows are uneconomical due to very small temperature drop achieved. Therefore, the number of rows is limited and the air is then cooled to a temperature higher than T_2 .

Low velocity of air allows adequate time for cooling. But low velocity causes laminar flow and also requires a higher cross-section of coil for adequate airflow. So velocity has to be of reasonably high value. Thus, air cannot be cooled to coil temperature by low air velocity.

$$[\text{Cooling capacity of coil} = \text{Mass flow rate of air} \times \text{specific heat} \times (T_1 - T_2)] \quad (2.4)$$

It can also be calculated by using the standard values of specific heat and representative specific volume to give a formula,

$$\text{Cooling capacity} = 0.0204 \times m^3/\text{min} \times (T_1 - T_2) \text{ kw} \quad (2.5)$$

It can also be

$$\text{Cooling capacity} = \text{mass flow in kg/s} \times (h_1 - h_2) \text{ kw} \quad (2.6)$$

EXAMPLE 2.3 Moist air having DBT and WBT of 40°C and 20°C, respectively flows over a cooling coil at the rate of 7000 m³/h. Finally, it is cooled to 26°C DBT. Plot the process on psychrometric chart and determine:

- (a) Final WBT of air.
- (b) The total heat transferred in kW.

If the cooling coil surface temperature is 22°C, find the bypass factor of the coil.

Solution: The process is as plotted on psychrometric chart shown in Figure 2.4(b). The point A is located on the chart at the intersection of 40°C DBT and 20°C WBT lines. Now the values: $h_A = 57.5$ kJ/kg dry air and $h_B = 41.5$ kJ/kg dry, $v_1 = 0.396$ m³/kg dry air

- (a) WBT of air at outlet = 15.5°C
- (b) Mass flow rate of air,

$$m_a = 7000 / (0.896 \times 3600) = 2.17 \text{ kg/s}$$

$$\begin{aligned} \text{Total heat transfer rate} &= (m_a)(h_A - h_B) \\ &= (2.17)(57.5 - 41.5) = 34.72 \text{ kW} \end{aligned}$$

$$\text{Bypass factor} = \frac{T_2 - T_3}{T_1 - T_3} = \frac{26 - 22}{40 - 22} = 0.22$$

2.3 Cooling and Dehumidification of Moist Air:

Here air is to be cooled and during cooling water vapor is to be separated from the air. Moisture separation will occur only when moist air is cooled to a temperature below its dew point temperature. Therefore, the effective surface temperature of the cooling coil kept below the initial dew point temperature of the air is called Apparatus Dew Point (ADP).

A cooling coil is shown schematically in Figure 2.4(a) and air flows uniformly across the coil. The process of cooling the air from state 1 to state 2 is as shown in Figure 2.4(b), while the coil surface temperature is kept at ADP. Although moisture separation occurs at various temperatures ranging from the initial dew point to final saturation temperature, it is assumed that the condensate water is

cooled to the final air temperature T_2 before it drains from the system under steady state.

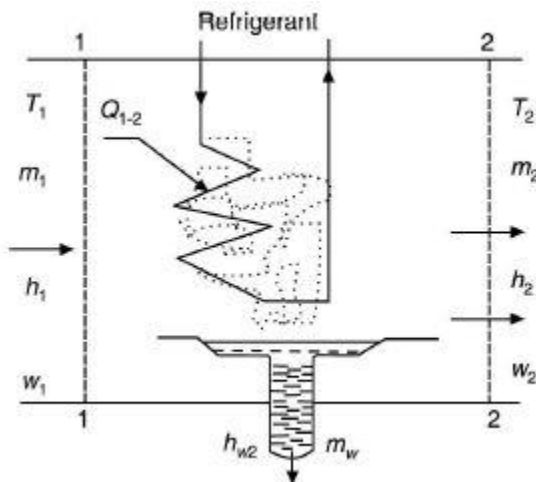


Figure 2.4(a) Schematic device for cooling and
Dehumidification

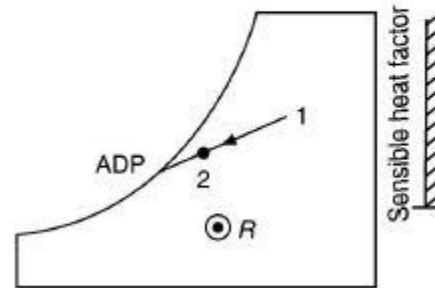


Figure 2.4(b) Cooling and dehumidification
on chart

Cooling the air to the coil surface temperature becomes uneconomical as the size of the heat exchanger becomes very large as (ΔT) reducer. Therefore, surface area of the coil is so designed that it will have a certain bypass factor given by following formal.

$$BF = \frac{T_2 - ADP}{T_1 - ADP} \quad (2.7)$$

For the system shown in Figure 2.4(a), the energy and mass balance equation are

$$m_1 h_1 = m_2 h_2 + Q_{1-2} + h_w m_w$$

$m_2 = (m_1 - m_w)$ but m_w is very small, therefore $m_2 = m_1$ considered approximately correct.

$$m_1 h_1 = m_2 h_2 + Q_{1-2} + m_w h_w \quad (2.8)$$

and $m_1 w_1 = m_1 w_2 + m_w \quad (2.9)$

$$m_w = m_1 (w_1 - w_2) \quad (2.10)$$

$$Q_{1-2} = m_1 [(h_1 - h_2) - (w_1 - w_2) h_{w2}] \quad (2.11)$$

- In any cooling and dehumidification process, both sensible and latent heats need to be rejected and this is carried out by the cooling fluid circulated through the coil.
- The sum of sensible and latent heat is the total heat transferred.
- The ratio of sensible heat to the total heat transfer is known as the *Coil Sensible Heat Factor (CSHF)*

The CSHF can be obtained by drawing a line on the psychometric chart parallel to the line marked on the protractor. (Line AB on the chart in Figure 2.5 is parallel to line ab on the protractor).

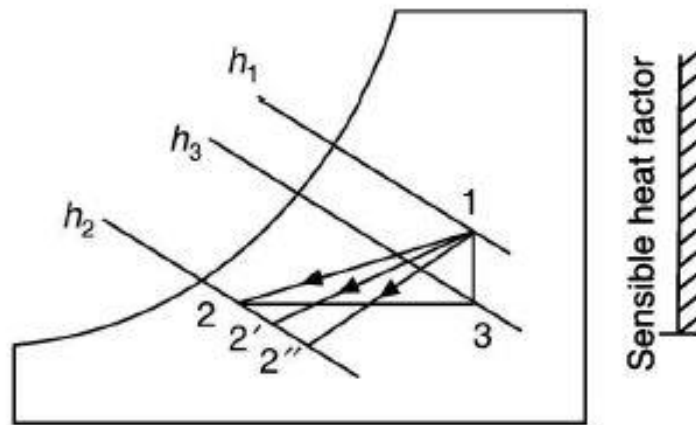


Figure 2.5 Sensible heat factor

By knowing CSHF, we can find the sensible heat and latent heat quantities.

$$CSHF = \frac{\text{Sensible heat}}{\text{Total heat}} = \frac{Q_s}{Q_t}$$

The enthalpy difference ($h_1 - h_2$) represents the total heat absorbed by the coil. In the processes 1-2, 1-2', 1-2'' the total heat absorbed is same but the proportion of sensible heat absorbed to total heat absorbed successively reduces. This is indicated by the fact that $T_2'' > T_2' > T_2$.

This proportion is called the *Sensible Heat Factor (SHF)*.

SHF represents the slope of the line representing the process on the psychometric chart so. From Figure 2.5 it can be said that

$$SHF = \frac{h_3 - h_2}{h_1 - h_2} \quad (2.12)$$

$$\tan \Theta = \Delta w / \Delta T$$

We see that Θ is the slope of the SHF line 1-2 on the psychometric chart which is purely a function of SHF, Thus, when a process line is to be drawn on the psychometric chart, the following two things have to be known.

- Initial state of air
- Sensible heat factor

For the construction of SHF line on the psychometric chart, one of the following methods can be used.

- (i) In the first method, calculate $\tan \Theta$, Then move vertically a certain distance Δw from the initial state, and then horizontally a distance,

$$\Delta T = (\Delta w)(\tan \Theta)$$

Lastly, join the point obtained to the initial state point. However, this method is prone to a grave error since Δw is numerically small, and $\tan \Theta$ tends to a value close to zero. The method is given here only to illustrate the principle involved; in practice it cannot be used.

- (ii) In the second method, move vertically a certain enthalpy change Δh_L . This is proportional to the latent heat change. Then move horizontally equivalent to the sensible heat change (Δh_s) in term of enthalpy given by:

$$\Delta h_s = (\Delta h_L) \left[\frac{SHF}{1 - SHF} \right]$$

Again, join the final point to the initial point.

- (iii) The third method uses a monographic method with some charts in which a scale is provided for SHF. There is also a reference point (say point R in Figure 2.6) provided which is joined to the appropriate SHF on the scale. Then a line from the initial state point can be drawn parallel to the above line, which will give the required SHF line.

2.4 ADIABATIC COOLING OR COOLING WITH HUMIDIFICATION PROCESS

Adiabatic cooling is because of the water attaining the wet-bulb temperature of air due to constant evaporation. In some dry areas, the difference between dry-bulb and wet-bulb temperature is high enough to use well water as cooling medium in a coil. As the WB temperature is higher than the dew point of air, the process is sensible cooling.

Let us consider warm air blowing over the water surface as shown in Figure 2.7. The air gets cooled. For cooling, air has to lose the heat it possesses. The air physically contacts the water surface, therefore, in one way it dissipates heat to the water by conduction. Secondly, water particles separate from the water surface, evaporate and mix with the air. For the evaporation of water latent heat is to be supplied which actually comes from both air as well as water. Therefore, both air and water get cooled. The heat exchange process is only between the air and the water, so the system is said to be insulated. This process of cooling is known as adiabatic cooling. It is also *called evaporative cooling or cooling with humidification*. For this reason, water in an open lake or well is cooler than the surrounding.

The water surface can also be in the form of water spray as shown in Figure 2.7(a) to hasten evaporation and cooling.

During an adiabatic process no heat enters or leaves the system. Thus, the process line 1—2 on the psychometric chart is along the constant enthalpy line.

The lowest possible temperature to which air can be cooled is the wet-bulb temperature (T_{wb}). Due to inefficient spray systems or uneconomical situations of providing a large number of banks of spray to get the cooling to T_{wb} , air is practically cooled to T_2 ($T_2 > T_{wb}$). The efficiency of spray is defined as

$$\text{Spray efficiency} = \frac{T_1 - T_2}{T_1 - T_{wb}} \quad (2.15)$$

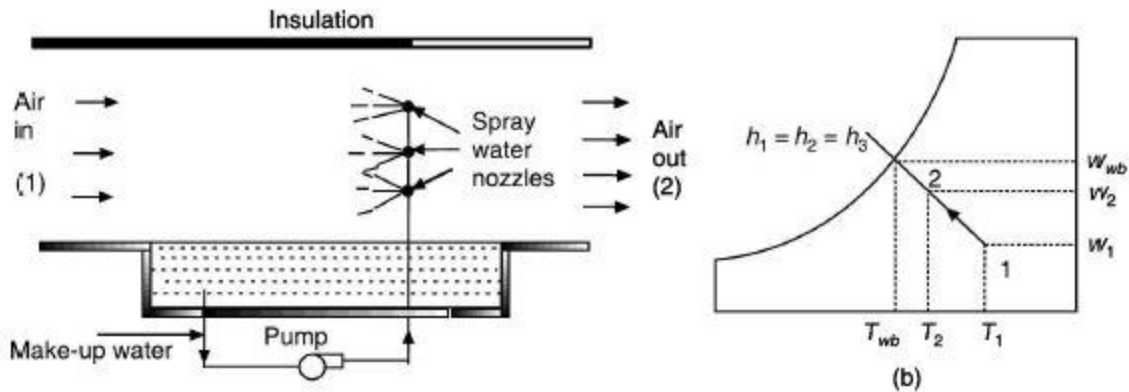


Figure 2.7(a) Adiabatic or evaporative cooling. Figure 2.7(b) Schematic diagram of Figure 2.7(a)

The water is recirculated with a pump. Make-up water is added to compensate for the water evaporated during with operation. The make-up water also known as *humidifier duty* in liter/h can be given by the formula,

$$\text{Humidifier duty} = \text{Make-up water}$$

$$= \text{mass rate of dry air in Kg/m}^3 \times (w_2 - w_1) \times 60 \text{ lit/h} \quad (2.16)$$

Where w_1 and w_2 are specific humidifies at conditions 1 and 2 in kg/kg of dry air.

humidifier duty can also written as

$$\text{humidifier duty} = \frac{\text{m}^3/\text{min}}{\text{specific volume}} = (w_2 - w_1) \times 60 \quad (2.17)$$

This is the process used in air coolers/desert coolers. Here the water surface is increased by spreading water over fiber pads. The efficiency of this cooler depends upon the thickness and uniform distribution of fibers in the pad. The extent of cooling, i.e. drop in temperature, depends upon the difference between DB and WB temperature. Therefore, air-cooling is higher in dry climate where this difference is large. This process is also used in cooling towers for cooling of condenser water.

Example 2.4: Moist air at 32° C DBT and 50% RH enters a cooling coil at 10.000 m³/h. It is desired that air leaving the coil has a DBT of 20° C and WBT of 18° C. Determine the following :

- Mean effective surface temperature of the coil.
- Bypass factor of the coil.
- Sensible heat factor of the coil.
- Total heat removed from air.
- Mass of water vapor condensed.

Solution: Figure 2.8 shows the schematic solution.

State A is located at the intersection of DBT of 32°C and RH=50%. Thus, $h_A = 70$ kJ/kg dry air and $w_A = 15.0$ g moisture /kg dry air and $v_A = 0.885$ m³/kg dry air.

State B is located at the intersection of DBT of 20°C line and WBT of 18°C line. Therefore, $h_B = 51.0$ kJ/kg dry air, $w_B = 12.0$ g moisture /kg dry air. From steam tables h_{wb-sat} corresponding to temperature 17°C DPT=71.3kJ/kg.

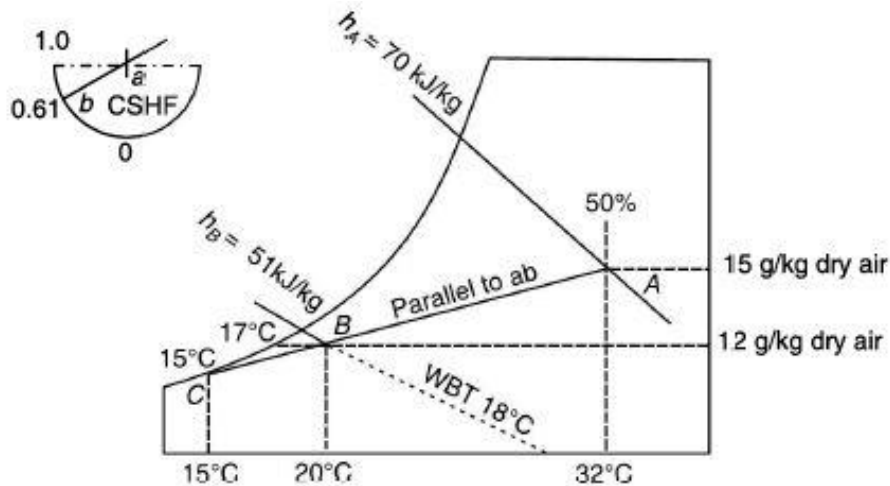


Figure 2.8 Schematic solution for Example 2.4

- Extend the line AB to meet the saturation curve at point C which indicates the mean effective surface temperature of 15° C. **Ans.**
- The coil bypass factor $= \frac{TB - T_c}{TA - T_c} = \frac{20 - 15}{32 - 15} = 0.29$ **Ans.**
- To get the sensible heat factor of the cooling coil, draw a line parallel to the process line AB through the center of the protractor given on

the chart, Then read the CSHF scale on the protractor, which is 0.61 in this case. **Ans.**

(d) Total heat removed per kilogram air:

$$m_A = (10.000)/(0.885 \times 3600) \\ = 3.13 \text{ kg/s}$$

$$q_{A-B} = 3.13 [(70-51) - (0.015-0.012) \times 71.3] = 58.8 \text{ kw} \quad \text{Ans.}$$

(e) Mass of water vapor condensed:

$$= m_A (w_A - w_B) = (3.31)(0.015-0.012) = 0.009 \text{ kg/s} \quad \text{Ans.}$$

2.5 HEATING AND HUMIDIFICATION

In this case both heat as well as water vapor are added to the air. To achieve this, the temperature of water to be sprayed in the air stream is kept at a temperature greater than the DBT of incoming air so that heat will be transferred to air to heat it. The unsaturated air reaches the condition of saturation and the heat of vaporization of water is absorbed from the spray water itself so that the spray water gets cooled. The heating and humidification process is shown in Figure 2.9.

During this process, the humidity ratio, the dry-bulb temperature, the wet-bulb temperature, the dew point temperature and the enthalpy of air increase while passing through hot spray. The relative humidity may increase or decrease. The spray water is to be heated before being pumped to the spray nozzles. The air enters at state 1 and leaves at state 2, as shown in Figure 2.9.

The mass balance for water is:

$$(m_{w1} - m_{w2}) = m (w_2 - w_1) \quad (2.18)$$

Where m_{w1} , m_{w2} are the mass flow rates of water entering and leaving in kg/min, respectively,

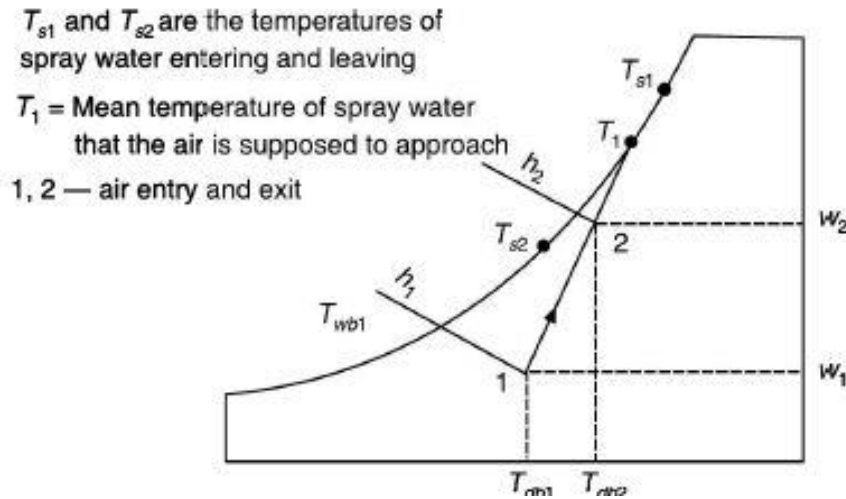


Figure 2.9. Heating and humidification with water spray

m , is the mass flow rate of air in kg/min, and w_1 and w_2 are specific humidity of air entering and leaving respectively.

The enthalpy balance,

$$(m_{w1} \times h_{w1} - m_{w2} \times h_{w2}) = m (h_2 - h_1) \quad (2.19)$$

Where h_{w1} and h_{w2} are enthalpy of spray water entering and leaving respectively.

2.6 Heating and Humidification by Steam Injection

Steam is normally injected into fresh outdoor air to increase humidity. High humidity air is the requirement of textile mills. The process is shown in Figure 2.9. The process can be analyzed by considering mass and energy balances. If m_v is the mass of steam supplied which has enthalpy h_v , and m_a is the mass of dry air, the mass and enthalpy balances are given by

$$w_1 \times m_a + m_v = m_a w_2 \quad (2.20)$$

$$h_1 \times m_a + m_v \times h_v = m_a h_2 \quad (2.21)$$

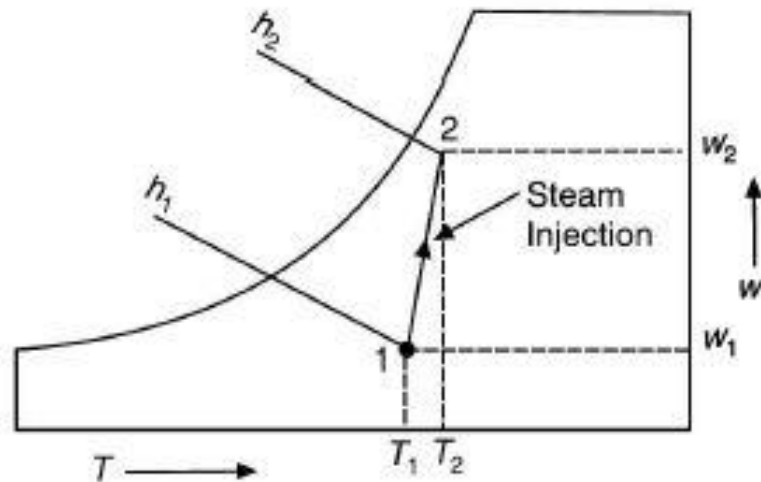


Figure 2.9. Heating and Humidification by Steam Injection

The dry-bulb temperature of air changes very little during the process.

Example 2.5 : Air enters a chamber at 10°C DBT and 5°C thermodynamic WBT at a rate of 100 cubic meter per minute (cmm). The barometer reads a pressure of 1.01325 bar. While passing through the chamber, the air absorbs sensible heat at the rate of 40.0 kw and picks up 45kg/h of saturated steam at 105°C . Determine the dry and wet-bulb temperatures of the air leaving the chamber.

Solution: This is a case of simple heating and humidification of air by the addition of steam as shown in Figure 2.10(a). Specific volume of the air entering the chamber is $0.813 \text{ m}^3/\text{kg}$ dry air.

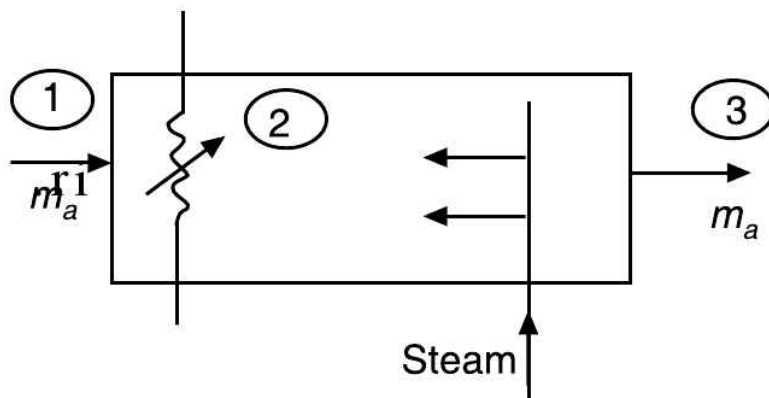


Figure 2.10(a). System for Example 2.5

The mass flow rate of air is:

$$m_a = \frac{(cmm)60}{v} = \frac{100 \times 60}{0.813} = 7380 \text{ kg dry air/h}$$

By moisture balance,

$$m_a (w_3 - w_1) = 45$$

$$w_3 = w_1 + \frac{45}{m_a} = 0.0032 + 45/7380$$

$$= 0.00929 \text{ kg w.v./kg dry air}$$

By energy balance,

$$m_a (h_3 - h_1) = (40.0)(3600) + 45h_v$$

Where $h_v = 2683.6 \text{ kJ/kg}$ is the enthalpy of saturated steam at 105°C .

Thus,

$$h_3 = 18.5 + 1/7380 [144,000 + 45 (2683.6)] = 54.375 \text{ kJ/kg dry air}$$

From psychrometric chart, at point 3

$$\text{DBT} = 26.5^\circ\text{C} \quad , \quad \text{WBT} = 18.1^\circ\text{C} \quad \text{Ans.}$$

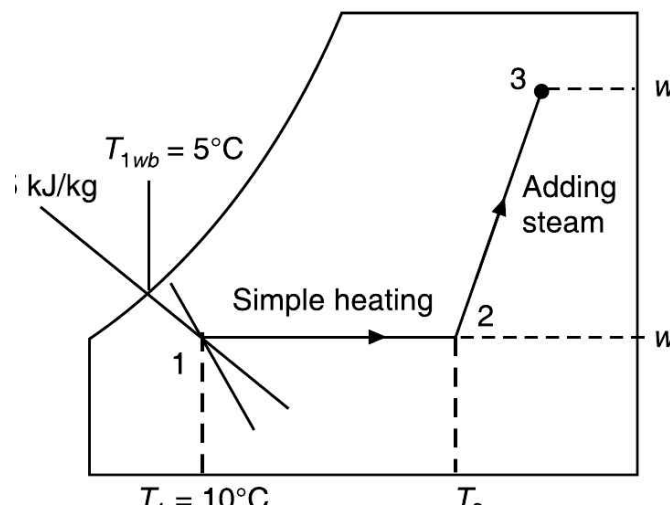


Figure 2.10(b). psychrometric processes for Example 2.5

2.7 ADIABATIC MIXING OF AIR STEAM

Mixing of two moist air streams is a common process in air-conditioning systems. For the purpose of analysis the mixing of two such streams is assumed to be an adiabatic process and is shown in Figure 2.11(a).

The pipelines carrying air streams are assumed to be perfectly insulated so that no heat enters or leaves the system Figure 2.11(b).

Heat balance gives

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \quad (2.22)$$

Mass balance gives

$$m_1 + m_2 = m_3 \quad (2.23)$$

Replacing the value of m_3 from Eq. (2.23) in Eq. (2.22)

$$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_3$$

Rearranging the terms,

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} \quad (2.24)$$

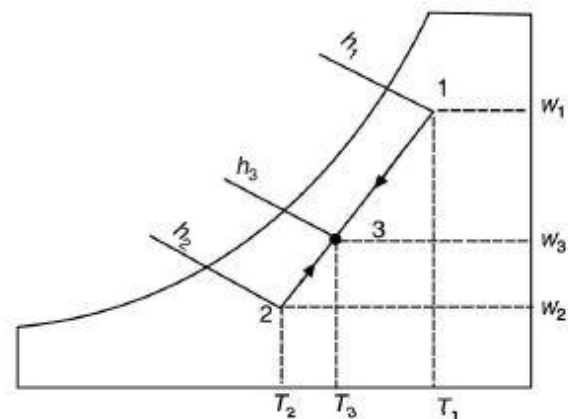
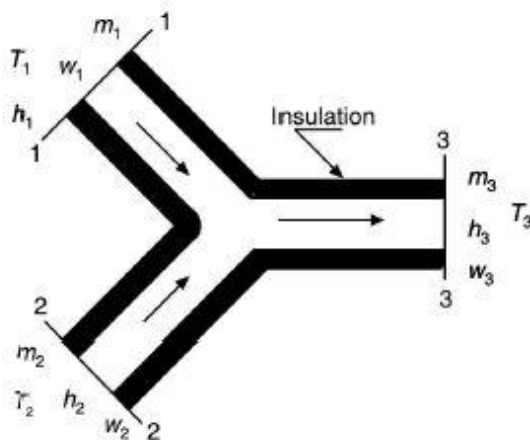


Figure 2.11(a) Adiabatic mixing of two moist streams

Figure 2.11(b) Adiabatic mixing of two air streams

Similarly, during mixing water vapor in neither added nor removed.

So,
$$m_1 w_1 + m_2 w_2 = m_3 w_3 \quad (2.25)$$

Substituting the value of m_3 and rearranging, we get

$$\frac{m_1}{m_2} = \frac{w_3 - w_2}{w_1 - w_3} \quad (2.26)$$

The symmetry also gives

$$\frac{m_1}{m_2} = \frac{T_3 - T_2}{T_1 - T_3} \quad (2.27)$$

When hot and high humid air is mixed with very cold air, the resulting mixture would contain fog and air mixture and the final condition (point 3 in Figure 2.12) on the psychometric chart would lie to the left or above the saturation curve. The temperature of the fog is corresponding to the wet bulb temperature line passing through point 3. The fog may also result when a very fine water spray is injected into air in a greater amount than required to saturate the air. Even a small quantity of steam injected into the air stream, which may not mix properly, would also result into fog.

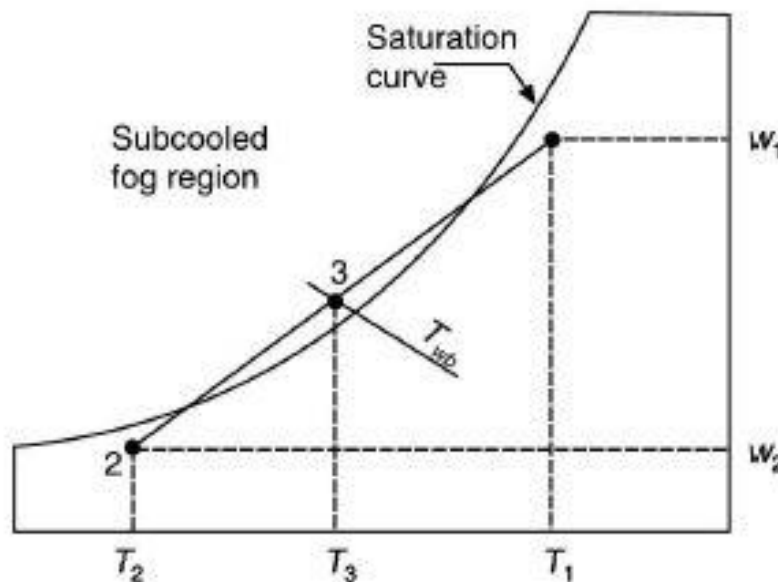


Figure 2.12 Adiabatic mixing of two air streams resulting into fog

Example 2.6 An air stream of 7000 m³/h at a DBT of 27°C and humidity ratio of 0.010 kg/kg dry air is adiabatically mixed with 120,000 m³/h of air having 35°C DBT and 55% RH. Find the DBT and WBT of the resulting mixture.

Solution: The process as shown in Figure 2.13 where states 1 and 2 are marked and the specific volumes v_1 and v_2 are 0.863 and 0.9 m³/kg, respectively.

$$m_1 = 7000 / (0.863 \times 3600) = 2.25 \text{ kg/s}$$

and $m_2 = 120,000 / (0.9 \times 3600) = 6.17 \text{ kg/s}$

$$\frac{\text{Line } 1-3}{\text{Line } 1-2} = \frac{m_1}{m_2} = \frac{2.25}{8.42} = 0.27$$

Consequently the length of line 1-3 = (0.27)(1-2). Accordingly, divide the line segment 1-2 to mark the point 3. The values of DBT and WBT at point 3 are read as 29°C and 20°C, respectively. **Ans.**

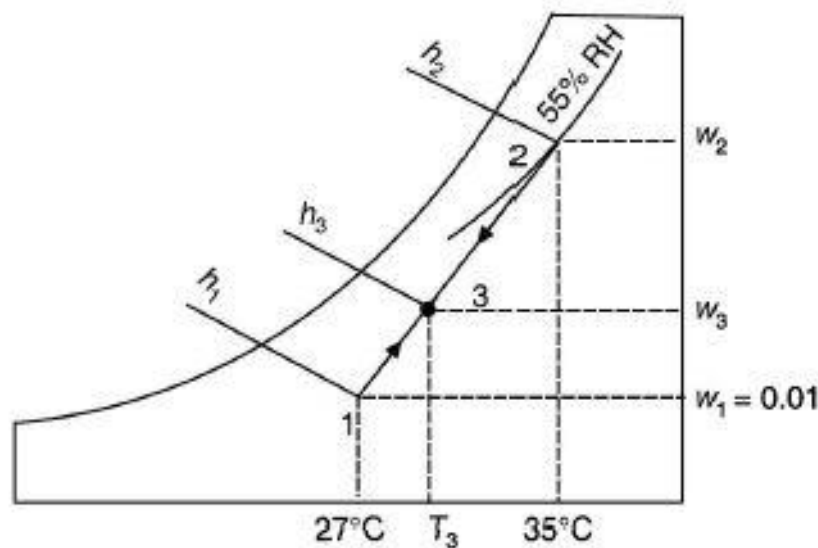


Figure 1.13 Adiabatic mixing of two air streams Example 2.6