# Lesson
# 28
# Psychrometric Processes

## The specific objectives of this lecture are to:

1. Introduction to psychrometric processes and their representation (*Section 28.1*)
2. Important psychrometric processes namely, sensible cooling and heating, cooling and dehumidification, cooling and humidification, heating and humidification, chemical dehumidification and mixing of air streams (*Section 28.2*)
3. Representation of the above processes on psychrometric chart and equations for heat and mass transfer rates (*Section 28.2*)
4. Concept of Sensible Heat Factor, By-pass Factor and apparatus dew point temperature of cooling coils (*Section 28.2.*)
5. Principle of air washers and various psychrometric processes that can be performed using air washers (*Section 28.3*)
6. Concept of enthalpy potential and its use (*Section 28.4*)

At the end of the lecture, the student should be able to:

1. Represent various psychrometric processes on psychrometric chart
2. Perform calculations for various psychrometric processes using the psychrometric charts and equations
3. Define sensible heat factor, by-pass factor, contact factor and apparatus dew point temperature
4. Describe the principle of an air washer and its practical use
5. Derive equation for total heat transfer rate in terms of enthalpy potential and explain the use of enthalpy potential

## 28.1. Introduction:

In the design and analysis of air conditioning plants, the fundamental requirement is to identify the various processes being performed on air. Once identified, the processes can be analyzed by applying the laws of conservation of mass and energy. All these processes can be plotted easily on a psychrometric chart. This is very useful for quick visualization and also for identifying the changes taking place in important properties such as temperature, humidity ratio, enthalpy etc. The important processes that air undergoes in a typical air conditioning plant are discussed below.

## 28.2. Important psychrometric processes:

a) Sensible cooling:

During this process, the moisture content of air remains constant but its temperature decreases as it flows over a cooling coil. For moisture content to remain constant, the surface of the cooling coil should be dry and its surface temperature should be greater than the dew point temperature of air. If the cooling coil is 100% effective, then the exit temperature of air will be equal to the coil temperature. However, in practice, the exit air temperature will be higher than the cooling coil temperature. Figure 28.1 shows the sensible cooling process O-A on a psychrometric chart. The heat transfer rate during this process is given by:

$$Q_c = m_a(h_O - h_A) = m_a c_{pm}(T_O - T_A) \qquad (28.1)$$

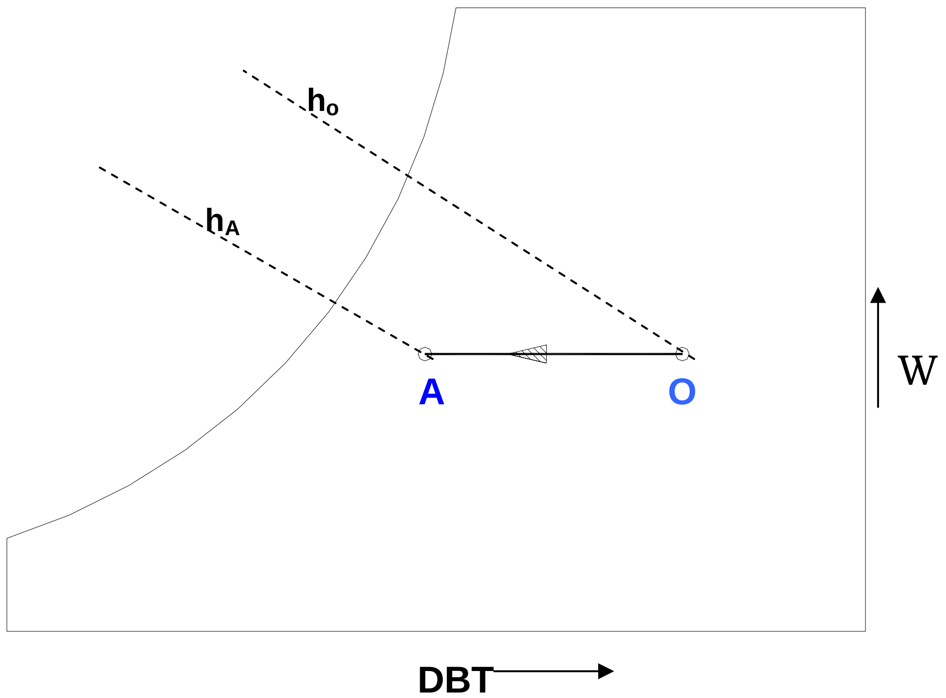


***Fig.28.1***: *Sensible cooling process O-A on psychrometric chart*

b) Sensible heating (Process O-B):

During this process, the moisture content of air remains constant and its temperature increases as it flows over a heating coil. The heat transfer rate during this process is given by:

$$Q_h = m_a(h_B - h_O) = m_a c_{pm}(T_B - T_O) \qquad (28.2)$$

where $c_{pm}$ is the humid specific heat (≈1.0216 kJ/kg dry air) and $m_a$ is the mass flow rate of dry air (kg/s). Figure 28.2 shows the sensible heating process on a psychrometric chart.

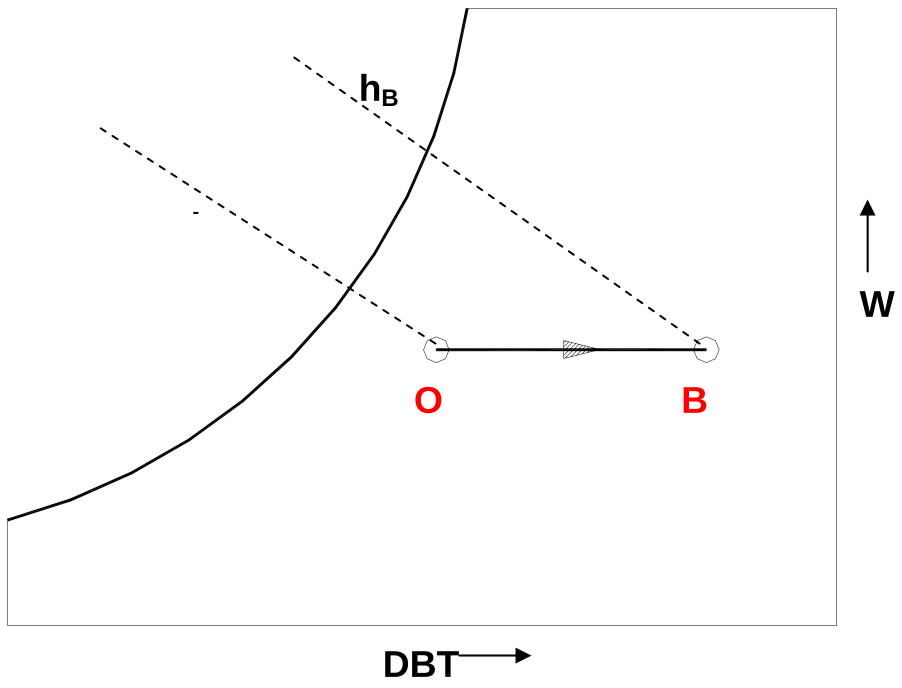


***Fig.28.2***: *Sensible heating process on psychrometric chart*

<u>c) Cooling and dehumidification (Process O-C):</u>

When moist air is cooled below its dew-point by bringing it in contact with a cold surface as shown in Fig.28.3, some of the water vapor in the air condenses and leaves the air stream as liquid, as a result both the temperature and humidity ratio of air decreases as shown. This is the process air undergoes in a typical air conditioning system. Although the actual process path will vary depending upon the type of cold surface, the surface temperature, and flow conditions, for simplicity the process line is assumed to be a straight line. The heat and mass transfer rates can be expressed in terms of the initial and final conditions by applying the conservation of mass and conservation of energy equations as given below:

By applying mass balance for the water:

$$\mathbf{m_a . w_O = m_a . w_C + m_w} \qquad (28.3)$$

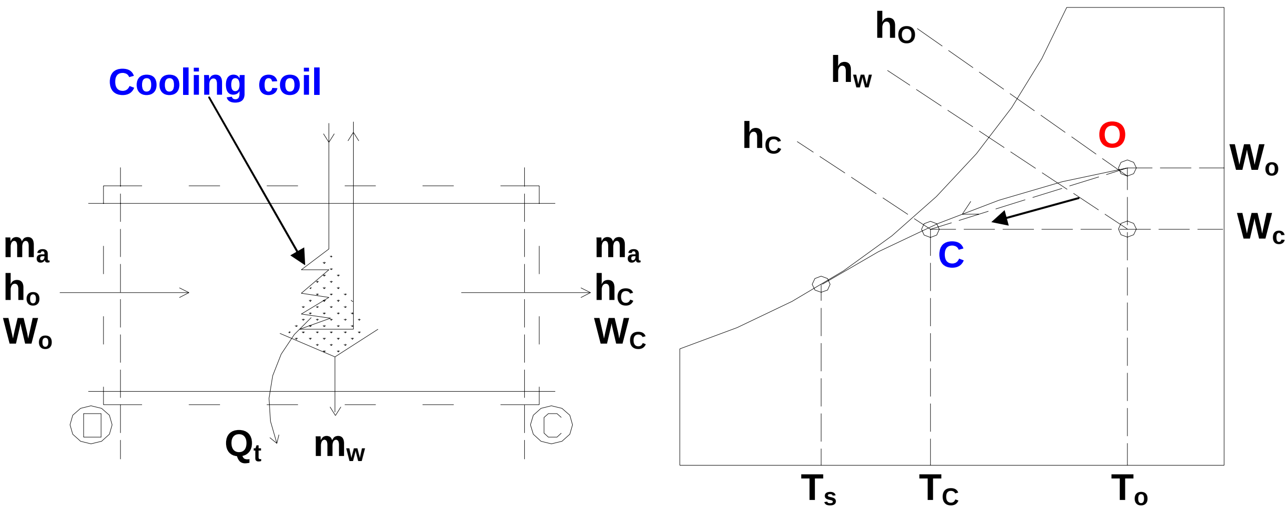


***Fig.28.3**: Cooling and dehumidification process (O-C)*

By applying energy balance:

$$m_a.h_O = Q_t + m_w.h_w + m_a.h_C \qquad (28.4)$$

from the above two equations, the load on the cooling coil, $Q_t$ is given by:

$$Q_t = m_a(h_O - h_C) - m_a(w_O - w_C)h_w \qquad (28.5)$$

the 2nd term on the RHS of the above equation is normally small compared to the other terms, so it can be neglected. Hence,

$$Q_t = m_a(h_O - h_C) \qquad (28.6)$$

It can be observed that the cooling and de-humidification process involves both latent and sensible heat transfer processes, hence, the total, latent and sensible heat transfer rates ($Q_t$, $Q_l$ and $Q_s$) can be written as:

$$\begin{aligned} & Q_t = Q_l + Q_s \\ \text{where} \quad & Q_l = m_a(h_O - h_w) = m_a.h_{fg}(w_O - w_C) \qquad (28.7) \\ & Q_s = m_a(h_w - h_C) = m_a.c_{pm}(T_O - T_C) \end{aligned}$$

By separating the total heat transfer rate from the cooling coil into sensible and latent heat transfer rates, a useful parameter called Sensible Heat Factor (SHF) is defined. SHF is defined as the ratio of sensible to total heat transfer rate, i.e.,

$$SHF = Q_s / Q_t = Q_s /(Q_s + Q_l) \qquad (28.8)$$

From the above equation, one can deduce that a SHF of 1.0 corresponds to no latent heat transfer and a SHF of 0 corresponds to no sensible heat transfer. A SHF of 0.75 to 0.80 is quite common in air conditioning systems in a normal dry-climate. A lower value of SHF, say 0.6, implies a high latent heat load such as that occurs in a humid climate.

From Fig.28.3, it can be seen that the slope of the process line O-C is given by:

$$\tan c = \frac{\Delta w}{\Delta T} \tag{28.9}$$

From the definition of SHF,

$$\frac{1-SHF}{SHF} = \frac{Q_l}{Q_s} = \frac{m_a h_{fg} \Delta w}{m_a c_{pm} \Delta T} = \frac{2501 \Delta w}{1.0216 \Delta T} = 2451 \frac{\Delta w}{\Delta T} \tag{28.10}$$

From the above equations, we can write the slope as:

$$\tan c = \frac{1}{2451}\left(\frac{1-SHF}{SHF}\right) \tag{28.11}$$

Thus we can see that the slope of the cooling and de-humidification line is purely a function of the sensible heat factor, SHF. Hence, we can draw the cooling and de-humidification line on psychrometric chart if the initial state and the SHF are known. In some standard psychrometric charts, a protractor with different values of SHF is provided. The process line is drawn through the initial state point and in parallel to the given SHF line from the protractor as shown in Fig.28.4.

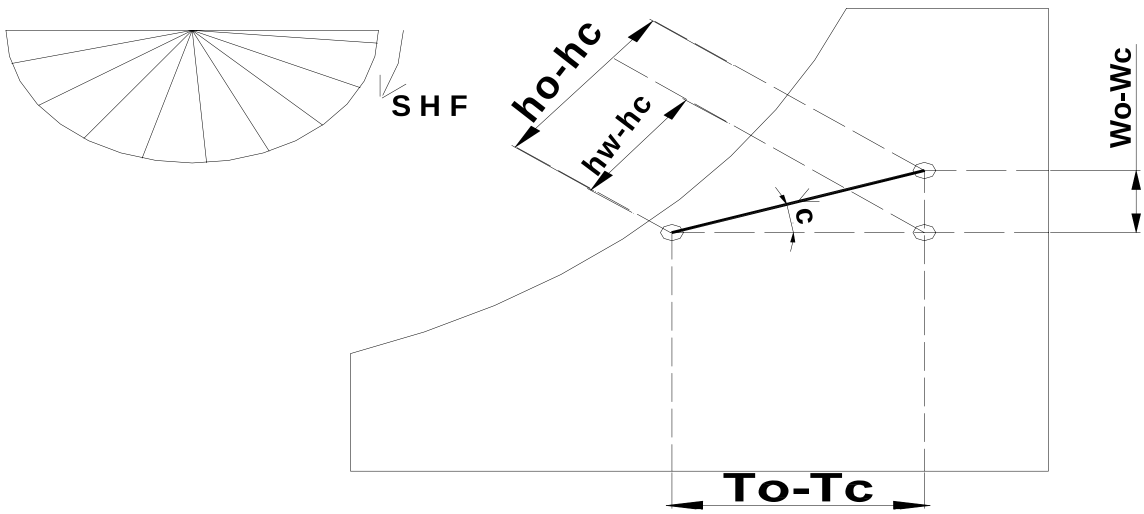


***Fig.28.4***: *A psychrometric chart with protractor for SHF lines*

In Fig.28.3, the temperature $T_s$ is the effective surface temperature of the cooling coil, and is known as apparatus dew-point (ADP) temperature. In an ideal situation, when all the air comes in perfect contact with the cooling coil surface, then the exit temperature of air will be same as ADP of the coil. However, in actual case the exit temperature of air will always be greater than the apparatus dew-point temperature due to boundary layer development as air flows over the cooling coil surface and also due to temperature variation along the fins etc. Hence, we can define a by-pass factor (BPF) as:

$$\mathbf{BPF} = \frac{\mathbf{T_C - T_S}}{\mathbf{T_O - T_S}} \tag{28.12}$$

It can be easily seen that, higher the by-pass factor larger will be the difference between air outlet temperature and the cooling coil temperature. When BPF is 1.0, all the air by-passes the coil and there will not be any cooling or de-humidification. In practice, the by-pass factor can be increased by increasing the number of rows in a cooling coil or by decreasing the air velocity or by reducing the fin pitch.

Alternatively, a contact factor(CF) can be defined which is given by:

$$\mathbf{CF = 1 - BPF} \tag{28.13}$$

d) Heating and Humidification (Process O-D):

During winter it is essential to heat and humidify the room air for comfort. As shown in Fig.28.5., this is normally done by first sensibly heating the air and then adding water vapour to the air stream through steam nozzles as shown in the figure.

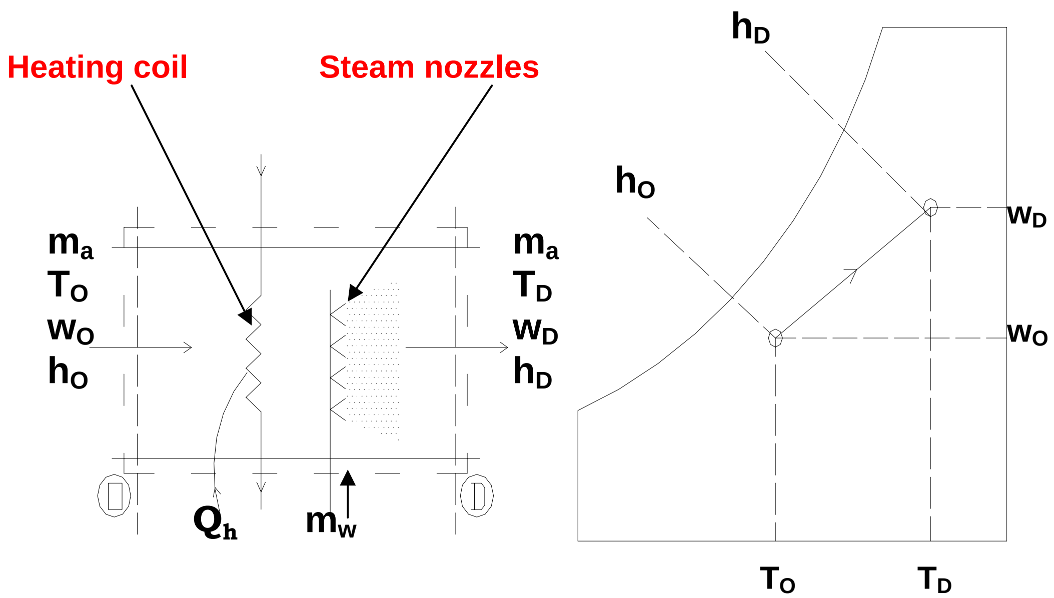


***Fig.28.5***: *Heating and humidification process*

Mass balance of water vapor for the control volume yields the rate at which steam has to be added, i.e., $m_w$:

$$\mathbf{m_w = m_a(w_D - w_O)} \tag{28.14}$$

where $m_a$ is the mass flow rate of dry air.

From energy balance:

$$Q_h = m_a(h_D - h_O) - m_w h_w \qquad (28.15)$$

where $Q_h$ is the heat supplied through the heating coil and $h_w$ is the enthalpy of steam.

Since this process also involves simultaneous heat and mass transfer, we can define a sensible heat factor for the process in a way similar to that of a coolind and dehumidification process.

e) Cooling & humidification (Process O-E):

As the name implies, during this process, the air temperature drops and its humidity increases. This process is shown in Fig.28.6. As shown in the figure, this can be achieved by spraying cool water in the air stream. The temperature of water should be lower than the dry-bulb temperature of air but higher than its dew-point temperature to avoid condensation ($T_{DPT} < T_w < T_O$).

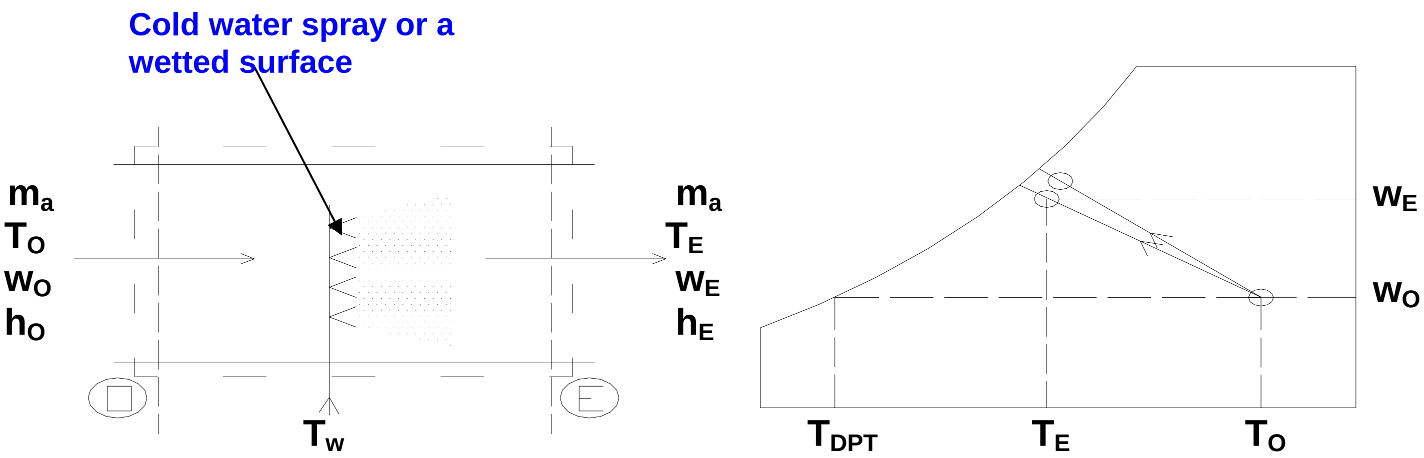


***Fig.28.6***: *Cooling and humdification process*

It can be seen that during this process there is sensible heat transfer from air to water and latent heat transfer from water to air. Hence, the total heat transfer depends upon the water temperature. If the temperature of the water sprayed is equal to the wet-bulb temperature of air, then the net transfer rate will be zero as the sensible heat transfer from air to water will be equal to latent heat transfer from water to air. If the water temperature is greater than WBT, then there will be a net heat transfer from water to air. If the water temperature is less than WBT, then the net heat transfer will be from air to water. Under a special case when the spray water is entirely recirculated and is neither heated nor cooled, the system is perfectly insulated and the make-up water is supplied at WBT, then at steady-state, the air undergoes an adiabatic saturation process, during which its WBT remains constant. This is the process of adiabatic saturation discussed in Chapter 27. The process of cooling and humidification is encountered in a wide variety of devices such as evaporative coolers, cooling towers etc.

f) Heating and de-humidification (Process O-F):

This process can be achieved by using a hygroscopic material, which absorbs or adsorbs the water vapor from the moisture. If this process is thermally isolated, then the enthalpy of air remains constant, as a result the temperature of air increases as its moisture content decreases as shown in Fig.28.7. This hygroscopic material can be a solid or a liquid. In general, the absorption of water by the hygroscopic material is an exothermic reaction, as a result heat is released during this process, which is transferred to air and the enthalpy of air increases.

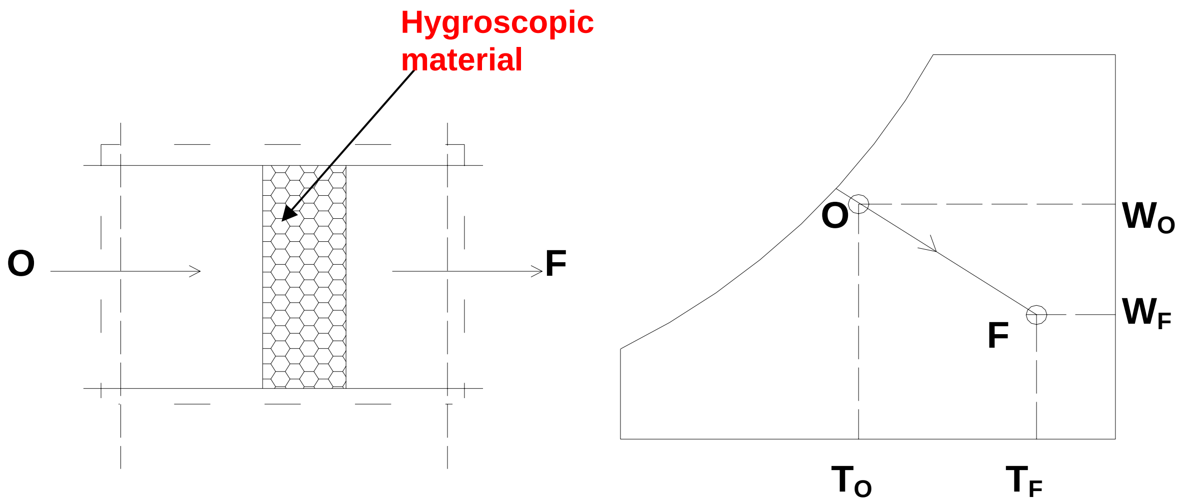


***Fig.28.7****. Chemical de-humidification process*

g) Mixing of air streams:

Mixing of air streams at different states is commonly encountered in many processes, including in air conditioning. Depending upon the state of the individual streams, the mixing process can take place with or without condensation of moisture.

i) Without condensation: Figure 28.8 shows an adiabatic mixing of two moist air streams during which no condensation of moisture takes place. As shown in the figure, when two air streams at state points 1 and 2 mix, the resulting mixture condition 3 can be obtained from mass and energy balance.

From the mass balance of dry air and water vapor:

$$\mathbf{m_{a,1}w_1 + m_{a,2}w_2 = m_{a,3}w_3 = (m_{a,1} + m_{a,2})w_3} \qquad (28.16)$$

From energy balance:

$$\mathbf{m_{a,1}h_1 + m_{a,2}h_2 = m_{a,3}h_3 = (m_{a,1} + m_{a,2})h_3} \qquad (28.17)$$

From the above equations, it can be observed that the final enthalpy and humidity ratio of mixture are weighted averages of inlet enthalpies and humidity ratios. A generally valid approximation is that the final temperature of the mixture is the weighted average of the inlet temperatures. With this approximation, the point on the psychrometric chart representing the mixture lies on a straight line connecting the two inlet states. Hence, the ratio of distances on the line, i.e., **(1-3)/(2-3)** is equal to the ratio of flow rates $\mathbf{m_{a,2}/m_{a,1}}$. The resulting error (due to the assumption that the humid specific heats being constant) is usually less than 1 percent.

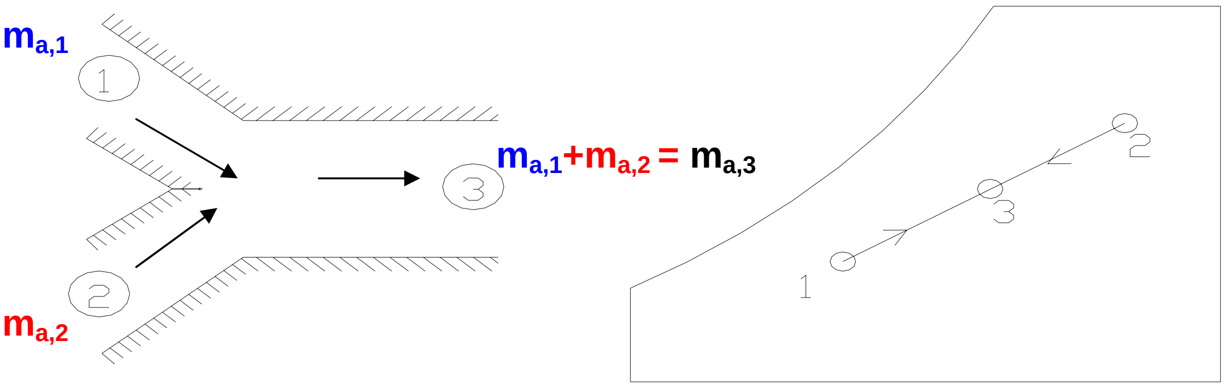


***Fig.28.8**. Mixing of two air streams without condensation*

ii) Mixing with condensation:

As shown in Fig.28.9, when very cold and dry air mixes with warm air at high relative humidity, the resulting mixture condition may lie in the two-phase region, as a result there will be condensation of water vapor and some amount of water will leave the system as liquid water. Due to this, the humidity ratio of the resulting mixture (point 3) will be less than that at point 4. Corresponding to this will be an increase in temperature of air due to the release of latent heat of condensation. This process rarely occurs in an air conditioning system, but this is the phenomenon which results in the formation of fog or frost (if the mixture temperature is below 0$^o$C). This happens in winter when the cold air near the earth mixes with the humid and warm air, which develops towards the evening or after rains.

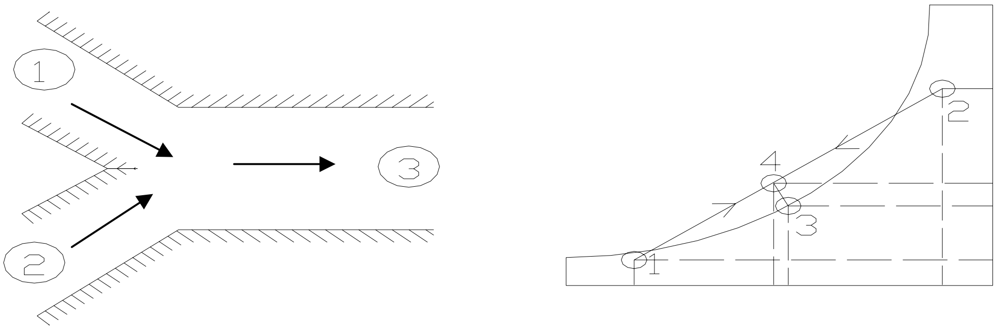


***Fig.28.9**. Mixing of two air streams with condensation*

## 28.3. Air Washers:

An air washer is a device for conditioning air. As shown in Fig.28.10, in an air washer air comes in direct contact with a spray of water and there will be an exchange of heat and mass (water vapour) between air and water. The outlet condition of air depends upon the temperature of water sprayed in the air washer. Hence, by controlling the water temperature externally, it is possible to control the outlet conditions of air, which then can be used for air conditioning purposes.

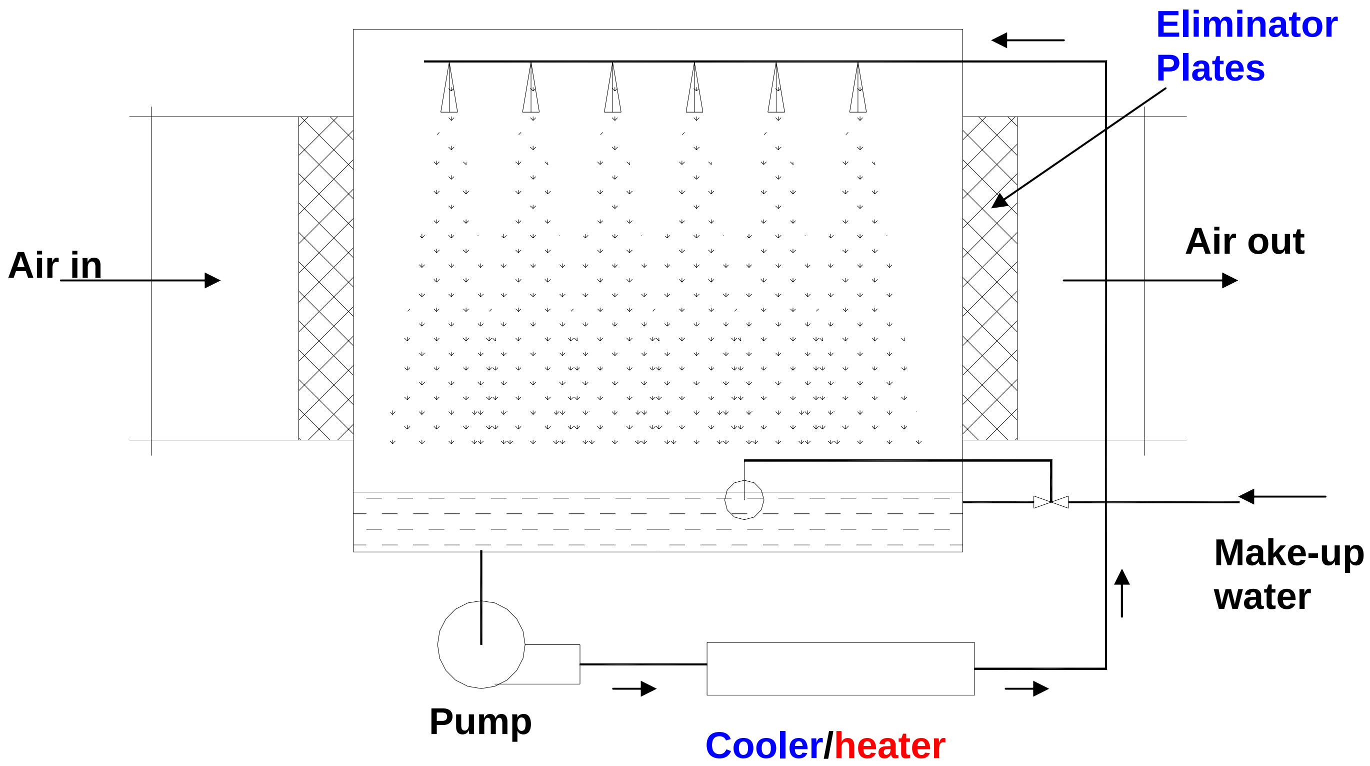


***Fig.28.10**: Air washer*

In the air washer, the mean temperature of water droplets in contact with air decides the direction of heat and mass transfer. As a consequence of the 2nd law, the heat transfer between air and water droplets will be in the direction of decreasing temperature gradient. Similarly, the mass transfer will be in the direction of decreasing vapor pressure gradient. For example,

a) Cooling and dehumidification: $t_w < t_{DPT}$. Since the exit enthalpy of air is less than its inlet value, from energy balance it can be shown that there is a transfer of total energy from air to water. Hence to continue the process, water has to be externally cooled. Here both latent and sensible heat transfers are from air to water. This is shown by Process O-A in Fig.28.11.

b) Adiabatic saturation: $t_w = t_{WBT}$. Here the sensible heat transfer from air to water is exactly equal to latent heat transfer from water to air. Hence, no external cooling or heating of water is required. That is this is a case of pure water recirculation. This is shown by Process O-B in Fig.28.11. This the process that takes place in a perfectly insulated evaporative cooler.

<u>c) Cooling and humidification: $t_{DPT} < t_w < t_{WBT}$.</u> Here the sensible heat transfer is from air to water and latent heat transfer is from water to air, but the total heat transfer is from air to water, hence, water has to be cooled externally. This is shown by Process O-C in Fig.28.11.

<u>d) Cooling and humidification: $t_{WBT} < t_w < t_{DBT}$.</u> Here the sensible heat transfer is from air to water and latent heat transfer is from water to air, but the total heat transfer is from water to air, hence, water has to be heated externally. This is shown by Process O-D in Fig.28.11. This is the process that takes place in a cooling tower. The air stream extracts heat from the hot water coming from the condenser, and the cooled water is sent back to the condenser.

<u>e) Heating and humidification: $t_w > t_{DBT}$.</u> Here both sensible and latent heat transfers are from water to air, hence, water has to be heated externally. This is shown by Process O-E in Fig.28.11.

Thus, it can be seen that an air washer works as a year-round air conditioning system. Though air washer is a and extremely useful simple device, it is not commonly used for comfort air conditioning applications due to concerns about health resulting from bacterial or fungal growth on the wetted surfaces. However, it can be used in industrial applications.

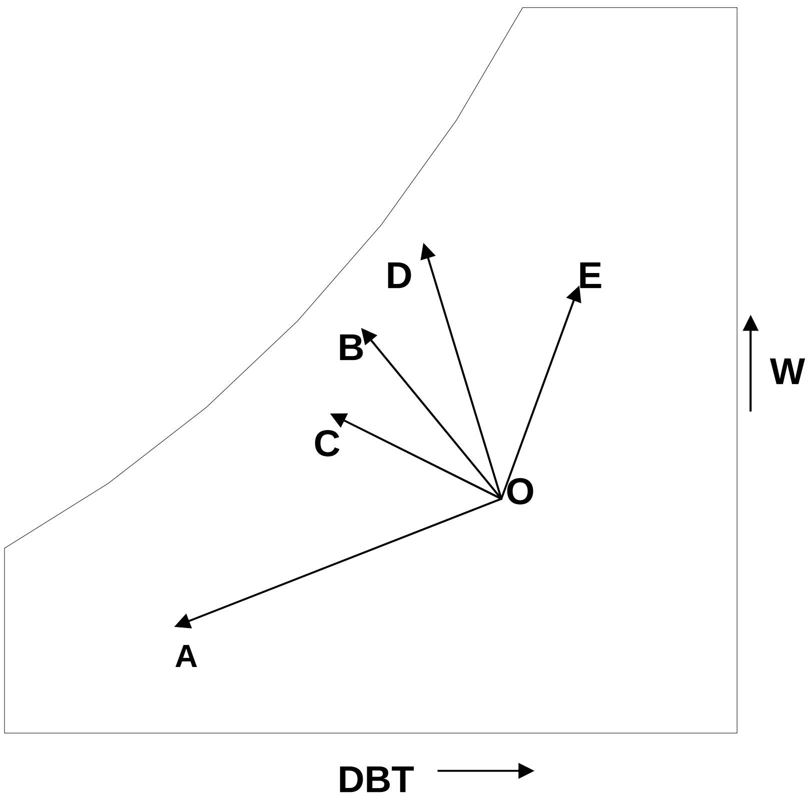


*Fig.28.11: Various psychrometric processes that can take place in an air washer*

## 28.4. Enthalpy potential:

As shown in case of an air washer, whenever water (or a wetted surface) and air contact each other, there is possibility of heat and moisture transfer between them. The directions of heat and moisture transfer depend upon the temperature and vapor pressure differences between air and water. As a result, the direction of the total heat transfer rate, which is a sum of sensible heat transfer and latent heat transfers also depends upon water and air conditions. The concept of enthalpy potential is very useful in quantifying the total heat transfer in these processes and its direction.

The sensible ($Q_S$) and latent ($Q_L$) heat transfer rates are given by:

$$\begin{aligned} Q_S &= h_C A_S (t_i - t_a) \\ Q_L &= \dot{m}_w . h_{fg} = h_D . A_S (w_i - w_a) . h_{fg} \end{aligned} \qquad (28.18)$$

the total heat transfer $Q_T$ is given by:

$$Q_T = Q_S + Q_L = h_C A_S (t_i - t_a) + h_D . A_S (w_i - w_a) . h_{fg} \qquad (28.19)$$

where $t_a$ = dry-bulb temperature of air, $^oC$

$t_i$ = temperature of water/wetted surface, $^oC$

$w_a$ = humidity ratio of air, kg/kg

$w_i$ = humidity ratio of saturated air at $t_i$, kg/kg

$h_c$ = convective heat transfer coefficient, W/m$^2$.$^o$C

$h_D$ = convective mass transfer coefficient, kg/m$^2$

$h_{fg}$ = latent heat of vaporization, J/kg

Since the transport mechanism that controls the convective heat transfer between air and water also controls the moisture transfer between air and water, there exists a relation between heat and mass transfer coefficients, $h_c$ and $h_D$ as discussed in an earlier chapter. It has been shown that for air-water vapor mixtures,

$$h_D \approx \frac{h_C}{c_{pm}} \text{ or } \frac{h_c}{h_D . c_{pm}} = \text{Lewis number} \approx 1.0 \qquad (28.20)$$

where $c_{pm}$ is the humid specific heat $\approx$ 1.0216 kJ/kg.K.

Hence the total heat transfer is given by:

$$Q_T = Q_S + Q_L = \frac{h_C A_S}{c_{pm}} \left[ (t_i - t_a) + (w_i - w_a) . h_{fg} \right] \qquad (28.21)$$

by manipulating the term in the parenthesis of RHS, it can be shown that:

$$Q_T = Q_S + Q_L = \frac{h_c A_S}{c_{pm}}[(h_i - h_a)] \quad (28.22)$$

thus the total heat transfer and its direction depends upon the enthalpy difference (or potential) between water and air ($h_i$-$h_a$).

**if $h_i > h_a$;** then the total heat transfer is from water to air and water gets cooled

**if $h_i < h_a$;** then the total heat transfer is from air to water and water gets heated

**if $h_i = h_a$;** then the net heat transfer is zero, i.e., the sensible heat transfer rate is equal to but in the opposite direction of latent heat transfer. Temperature of water remains at its wet bulb temperature value

The concept of enthalpy potential is very useful in psychrometric calculations and is frequently used in the design and analysis of evaporative coolers, cooling towers, air washers etc.

## Questions and answers:

**1.** Which of the following statements are TRUE?

a) During sensible cooling of air, both dry bulb and wet bulb temperatures decrease

b) During sensible cooling of air, dry bulb temperature decreases but wet bulb temperature remains constant

c) During sensible cooling of air, dry and wet bulb temperatures decrease but dew point temperature remains constant

d) During sensible cooling of air, dry bulb, wet bulb and dew point temperatures decrease

**Ans.: a) and c)**

**2.** Which of the following statements are TRUE?

a) The sensible heat factor for a sensible heating process is 1.0

b) The sensible heat factor for a sensible cooling process is 0.0

c) Sensible heat factor always lies between 0.0 and 1.0

d) Sensible heat factor is low for air conditioning plants operating in humid climates

**Ans.: a) and d)**

**3.** Which of the following statements are TRUE?

a) As the by-pass factor (BPF) of the cooling coil increases, temperature difference between air at the outlet of the coil and coil ADP decreases

b) The BPF of the coil increases as the velocity of air through the coil increases

c) The BPF of the coil increases as the fin pitch increases

d) The BPF of the coil decreases as the number of rows in the flow direction increase

**Ans.: b), c) and d)**

**4.** Which of the following statements are TRUE?

a) During cooling and humidification process, the enthalpy of air decreases

b) During cooling and humidification process, the enthalpy of air increases

c) During cooling and humidification process, the enthalpy of air remains constant

d) During cooling and humidification process, the enthalpy of air may increase, decrease or remain constant depending upon the temperature of the wet surface

**Ans.: d)**

**5.** An air stream at a flow rate of 1 kg/s and a DBT of $30^oC$ mixes adiabatically with another air stream flowing with a mass flow rate of 2 kg/s and at a DBT of $15^oC$. Assuming no condensation to take place, the temperature of the mixture is approximately equal to:

a) $20^oC$

b) $22.5^oC$

c) $25^oC$

d) Cannot be found

**Ans.: a)**

**6.** Which of the following statements are TRUE?

a) In an air washer, water has to be externally cooled if the temperature at which it is sprayed is equal to the dry bulb temperature of air

b) In an air washer, water has to be externally heated if the temperature at which it is sprayed is equal to the dry bulb temperature of air

c) In an air washer, if water is simply recirculated, then the enthalpy of air remains nearly constant at steady state

d) In an air washer, if water is simply recirculated, then the moisture content of air remains nearly constant at steady state

**Ans.: b) and c)**

**7.** Which of the following statements are TRUE?

a) When the enthalpy of air is equal to the enthalpy of saturated air at the wetted surface temperature, then there is no sensible heat transfer between air and the wetted surface

b) When the enthalpy of air is equal to the enthalpy of saturated air at the wetted surface temperature, then there is no latent heat transfer between air and the wetted surface

c) When the enthalpy of air is equal to the enthalpy of saturated air at the wetted surface temperature, then there is no net heat transfer between air and the wetted surface

d) When the enthalpy of air is equal to the enthalpy of saturated air at the wetted surface temperature, then the wet bulb temperature of air remains constant

**Ans.: c) and d)**

**8.** What is the required wattage of an electrical heater that heats 0.1 $m^3/s$ of air from $15^oC$ and 80% RH to $55^oC$? The barometric pressure is 101.325 kPa.

**Ans.:** Air undergoes sensible heating as it flows through the electrical heater

From energy balance, the required heater wattage (W) is given by:

$$\mathbf{W = m_a(h_e - h_i) \approx (V_a/\nu_a).c_{pm}(T_e - T_i)}$$

Where $V_a$ is the volumetric flow rate of air in $m^3/s$ and $\nu_a$ is the specific volume of dry air. $T_e$ and $T_i$ are the exit and inlet temperatures of air and cpm is the average specific heat of moist air (**≈1021.6 J/kg.K**).

Using perfect gas model, the specific volume of dry air is found to be:

$$\mathbf{\nu_a = (R_a.T/P_a) = (R_a.T/(P_t - P_v))}$$

At $15^oC$ and 80% RH, the vapour pressure $p_v$ is found to be 1.364 kPa using psychrometric chart or equations.

Substituting the values of $R_a$, T, $p_t$ and $p_v$ in the equation for specific volume, we find the value of specific volume to be **0.8274 $m^3/kg$**

$$\therefore \mathbf{\text{Heater wattage, } W \approx (V_a/\nu_a).c_{pm}(T_e - T_i) = (0.1/0.8274) \times 1021.6(55-15) = 4938.8\ W}$$

**(ans.)**

**9.** 0.2 kg/s of moist air at 45°C (DBT) and 10% RH is mixed with 0.3 kg/s of moist air at 25°C and a humidity ratio of 0.018 kgw/kgda in an adiabatic mixing chamber. After mixing, the mixed air is heated to a final temperature of 40°C using a heater. Find the temperature and relative humidity of air after mixing. Find the heat transfer rate in the heater and relative humidity of air at the exit of heater. Assume the barometric pressure to be 1 atm.

**Ans.:** Given:

<u>Stream 1:</u> mass flow rate, $m_1$ = 0.2 kg/s; $T_1$ = 45°C and RH = 10%.

Using psychrometric equations or psychrometric chart, the humidity ratio and enthalpy of stream 1 are found to be:

$$\mathbf{W_1 = 0.006\ kgw/kgda\ \&\ h_1 = 61.0\ kJ/kgda}$$

<u>Stream 2:</u> mass flow rate, $m_2$ = 0.3 kg/s; $T_2$ = 45°C and $W_2$ = 0.018 kgw/kgda

Using psychrometric equations or psychrometric chart, enthalpy of stream 2 is found to be:

$$\mathbf{h_1 = 71.0\ kJ/kgda}$$

<u>For the adiabatic mixing process, from mass balance:</u>

$$W_3 = \frac{m_{a,1}w_1 + m_{a,2}w_2}{m_{a,1} + m_{a,2}} = \frac{0.2x0.006 + 0.3x0.018}{0.2 + 0.3} = 0.0132\ kgw/kgda$$

From energy balance (assuming the specific heat of moist air to remain constant):

$$T_3 = \frac{m_{a,1}T_1 + m_{a,2}T_2}{m_{a,1} + m_{a,2}} = \frac{0.2x45 + 0.3x25}{0.2 + 0.3} = 33^o C \qquad \textbf{(ans.)}$$

From $T_3$ and $W_3$, the relative humidity of air after mixing is found to be:

$$\mathbf{RH_3 = 41.8\%} \qquad \textbf{(ans.)}$$

For the sensible heating process in the heater:

$$\mathbf{Q_s = m_a(h_e - h_i) \approx m_a.c_{pm}(T_e - T_i) = 0.5x1.0216(40\text{-}33) = 3.5756\ kW} \quad \textbf{(ans.)}$$

The relative humidity at the exit of heater is obtained from the values of DBT (40°C) and humidity ratio (0.0132 kgw/kgda) using psychrometric chart/equations. This is found to be:

**RH at 40°C and 0.0132 kgw/kgda = 28.5 %** **(ans.)**

**10.** A cooling tower is used for cooling the condenser water of a refrigeration system having a heat rejection rate of 100 kW. In the cooling tower air enters at 35$^oC$ (DBT) and 24$^oC$ (WBT) and leaves the cooling tower at a DBT of 26$^oC$ relative humidity of 95%. What is the required flow rate of air at the inlet to the cooling tower in $m^3/s$. What is the amount of make-up water to be supplied? The temperature of make-up water is at 30$^oC$, at which its enthalpy ($h_w$) may be taken as 125.4 kJ/kg. Assume the barometric pressure to be 1 atm.

**Ans.:**

<u>At the inlet to cooling tower:</u> DBT = 35$^oC$ and WBT = 24$^oC$

From psychrometric chart/equations the following values are obtained for the inlet:

**Humidity ratio, $W_i$ = 0.01426 kgw/kgda**

**Enthalpy, $h_i$ = 71.565 kJ/kgda**

**Sp. volume, $\nu_i$ = 0.89284 $m^3$/kgda**

<u>At the outlet to cooling tower:</u> DBT = 26$^oC$ and RH = 95%

From psychrometric chart/equations the following values are obtained for the outlet:

**Humidity ratio, $W_o$ = 0.02025 kgw/kgda**

**Enthalpy, $h_i$ = 77.588 kJ/kgda**

From mass and energy balance across the cooling tower:

$$Q_c = m_a\{(h_o - h_i) - (W_o - W_i)h_w\} = 100 \text{ kW}$$

Substituting the values of enthalpy and humidity ratio at the inlet and outlet of cooling tower and enthalpy of make-up water in the above expression, we obtain:

**$m_a$ = 18.97 kg/s,**

**hence, the volumetric flow rate, $V_i = m_a \times \nu_i$ = 16.94 $m^3$/s (ans.)**

Amount of make-up water required mw is obtained from mass balance as:

**$m_w = m_a(W_o - W_i)$ = 18.97(0.02025 − 0.01426) = 0.1136 kg/s = 113.6 grams/s (ans.)**

**11.** In an air conditioning system air at a flow rate of 2 kg/s enters the cooling coil at 25$^oC$ and 50% RH and leaves the cooling coil at 11$^oC$ and 90% RH. The apparatus dew point of the cooling coil is 7$^oC$. Find a) The required cooling capacity of the coil, b) Sensible Heat Factor for the process, and c) By-pass factor of the cooling coil. Assume the barometric pressure to be 1 atm. Assume the condensate water to leave the coil at ADP ($h_w$ = 29.26 kJ/kg)

**Ans.:** At the inlet to the cooling coil; $T_i$ = 25$^oC$ and RH = 50%

From psychrometric chart; $W_i$ = 0.00988 kgw/kgda and $h_i$ = 50.155 kJ/kgda

At the outlet of the cooling coil; $T_o = 11^oC$ and RH = 90%

From psychrometric chart; $W_o = 0.00734$ kgw/kgda and $h_o = 29.496$ kJ/kgda

a) From mass balance across the cooling coil, the condesate rate, $m_w$ is:

$$\mathbf{m_w = m_a(W_i - W_o) = 2.0(0.00988 - 0.00734) = 0.00508\ kg/s}$$

From energy balance across the cooling tower, the required capacity of the cooling coil, $Q_c$ is given by:;

$$\mathbf{Q_c = m_a(h_i - h_o) - m_w.h_w = 2.0(50.155 - 29.496) - 0.00508 \times 29.26 = 41.17\ kW \quad (ans.)}$$

b) The sensible heat transfer rate, $Q_s$ is given by:

$$\mathbf{Q_s = m_a c_{pm}(T_i - T_o) = 2.0 \times 1.0216 \times (25 - 11) = 28.605\ kW}$$

The latent heat transfer rate, $Q_l$ is given by:

$$\mathbf{Q_s = m_a h_{fg}(W_i - W_o) = 2.0 \times 2501.0 \times (0.00988 - 0.00734) = 12.705\ kW}$$ [1]

The Sensible Heat Factor (SHF) is given by:

$$\mathbf{SHF = Q_s/(Q_s + Q_l) = 28.605/(28.605 + 12.705) = 0.692 \qquad (ans.)}$$

c) From its definition, the by-pass factor of the coil, BPF is given by:

$$\mathbf{BPF = (T_o - ADP)/(T_i - ADP) = (11 - 7)/(25 - 7) = 0.222 \qquad (ans.)}$$

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1 The small difference between $Q_c$ and $(Q_s + Q_l)$ is due to the use of average values for specific heat, $c_{pm}$ and latent heat of vaporization, $h_{fg}$.