

Lesson

31

Evaporative, Winter And All Year Air Conditioning Systems

The specific objectives of this lecture are to:

1. Introduce evaporative cooling systems (*Section 31.1*)
2. Classify evaporative cooling systems (*Section 31.2*)
3. Discuss the characteristics of direct evaporative cooling systems (*Section 31.2.1*)
4. Discuss the characteristics of indirect evaporative cooling systems (*Section 31.2.2*)
5. Discuss the characteristics of multi-stage evaporative cooling systems (*Section 31.2.3*)
6. Discuss advantages and disadvantages of evaporative cooling systems (*Section 31.3*)
7. Discuss the applicability of evaporative cooling systems (*Section 31.4*)
8. Describe winter air conditioning systems (*Section 31.5*)
9. Describe all year air conditioning systems (*Section 31.6*)

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

1. Explain the working principle of direct, indirect and multi-stage evaporative cooling systems
2. Perform psychrometric calculations on evaporative cooling systems
3. List the advantages and disadvantages of evaporative cooling systems
4. Evaluate the applicability of evaporative cooling systems based on climatic conditions
5. Describe winter air conditioning systems and perform psychrometric calculations on these systems
6. Describe all year air conditioning systems

31.1. Introduction to evaporative air conditioning systems:

Summer air conditioning systems capable of maintaining exactly the required conditions in the conditioned space are expensive to own and operate. Sometimes, partially effective systems may yield the best results in terms of comfort and cost. Evaporative air conditioning systems are inexpensive and offer an attractive alternative to the conventional summer air conditioning systems in places, which are hot and dry. Evaporative air conditioning systems also find applications in hot industrial environments where the use of conventional air conditioning systems becomes prohibitively expensive.

Evaporative cooling has been in use for many centuries in countries such as India for cooling water and for providing thermal comfort in hot and dry regions. This system is based on the principle that when moist but unsaturated air comes in contact with a wetted surface whose temperature is higher than the dew point temperature of air, some water from the wetted surface evaporates into air. The latent heat of evaporation is taken from

water, air or both of them. In this process, the air loses sensible heat but gains latent heat due to transfer of water vapour. Thus the air gets cooled and humidified. The cooled and humidified air can be used for providing thermal comfort.

31.2. Classification of evaporative cooling systems:

The principle of evaporative cooling can be used in several ways. Cooling can be provided by:

1. Direct evaporation process
2. Indirect evaporation process, or
3. A combination or multi-stage systems

31.2.1. Direct evaporative cooling systems:

In direct evaporative cooling, the process or conditioned air comes in direct contact with the wetted surface, and gets cooled and humidified. Figure 31.1 shows the schematic of an elementary direct, evaporative cooling system and the process on a psychrometric chart. As shown in the figure, hot and dry outdoor air is first filtered and then is brought in contact with the wetted surface or spray of water droplets in the air washer. The air gets cooled and dehumidified due to simultaneous transfer of sensible and latent heats between air and water (**process o-s**). The cooled and humidified air is supplied to the conditioned space, where it extracts the sensible and latent heat from the conditioned space (**process s-i**). Finally the air is exhausted at state i. In an ideal case when the air washer is perfectly insulated and an infinite amount of contact area is available between air and the wetted surface, then the cooling and humidification process follows the constant wet bulb temperature line and the temperature at the exit of the air washer is equal to the wet bulb temperature of the entering air ($t_{o,wbt}$), i.e., the process becomes an adiabatic saturation process. However, in an actual system the temperature at the exit of the air washer will be higher than the inlet wet bulb temperature due to heat leaks from the surroundings and also due to finite contact area. One can define the saturation efficiency or effectiveness of the evaporative cooling system ε as:

$$\varepsilon = \frac{(t_o - t_s)}{(t_o - t_{o,wbt})} \quad (31.1)$$

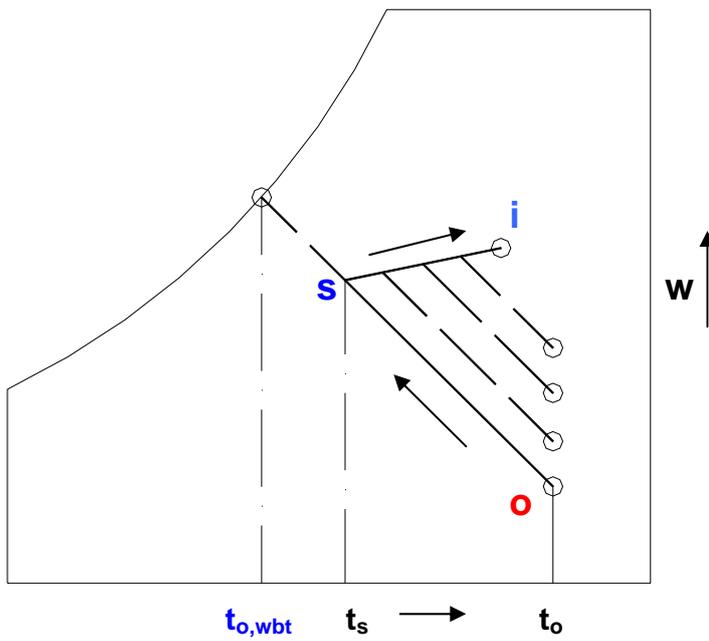
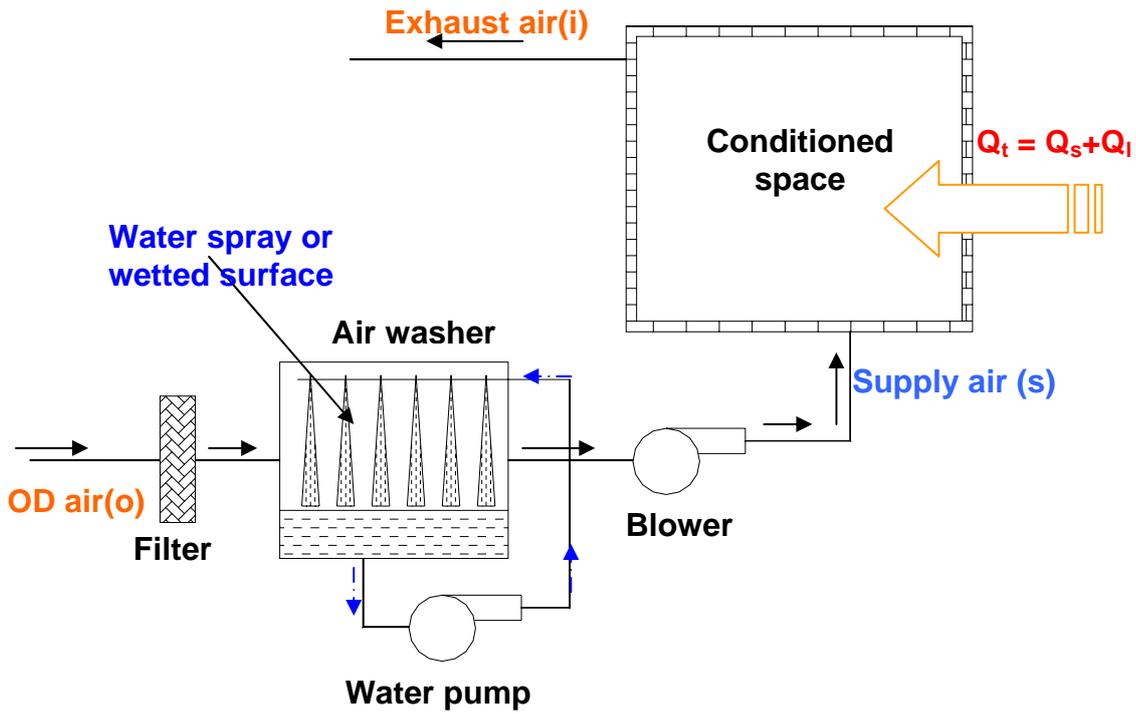


Fig.31.1: A direct, evaporative cooling system

Depending upon the design aspects of the evaporative cooling system, the effectiveness may vary from 50% (for simple drip type) to about 90% (for efficient spray pads or air washers).

The amount of supply air required \dot{m}_s can be obtained by writing energy balance equation for the conditioned space, i.e.,

$$\dot{m}_s = \frac{Q_t}{(h_i - h_s)} \quad (31.2)$$

where Q_t is the total heat transfer rate (sensible + latent) to the building, h_i and h_s are the specific enthalpies of return air and supply air, respectively.

Compared to the conventional refrigeration based air conditioning systems, the amount of airflow rate required for a given amount of cooling is much larger in case of evaporative cooling systems. As shown by the above equation and also from Fig.30.1, it is clear that for a given outdoor dry bulb temperature, as the moisture content of outdoor air increases, the required amount of supply air flow rate increases rapidly. And at a threshold moisture content value, the evaporative coolers cannot provide comfort as the cooling and humidification line lies above the conditioned space condition 'i'. Thus evaporative coolers are very useful essentially in dry climates, whereas the conventional refrigeration based air conditioning systems can be used in any type of climate.

31.2.2. Indirect evaporative cooling system:

Figure 30.2 shows the schematic of a basic, indirect evaporative cooling system and the process on a psychrometric chart. As shown in the figure, in an indirect evaporative cooling process, two streams of air - **primary and secondary** are used. The primary air stream becomes cooled and humidified by coming in direct contact with the wetted surface (**o-o'**), while the secondary stream which is used as supply air to the conditioned space, decreases its temperature by exchanging only sensible heat with the cooled and humidified air stream (**o-s**). Thus the moisture content of the supply air remains constant in an indirect evaporative cooling system, while its temperature drops. Obviously, everything else remaining constant, the temperature drop obtained in a direct evaporative cooling system is larger compared to that obtained in an indirect system, in addition the direct evaporative cooling system is also simpler and hence, relatively inexpensive. However, since the moisture content of supply air remains constant in an indirect evaporation process, this may provide greater degree of comfort in regions with higher humidity ratio. In modern day indirect evaporative coolers, the conditioned air flows through tubes or plates made of non-corroding plastic materials such as polystyrene (PS) or polyvinyl chloride (PVC). On the outside of the plastic tubes or plates thin film of water is maintained. Water from the liquid film on the outside of the tubes or plates evaporates into the air blowing over it (primary air) and cools the conditioned air flowing through the tubes or plates sensibly. Even though the plastic materials used in these

coolers have low thermal conductivity, the high external heat transfer coefficient due to evaporation of water more than makes up for this. The commercially available indirect evaporative coolers have saturation efficiency as high as 80%.

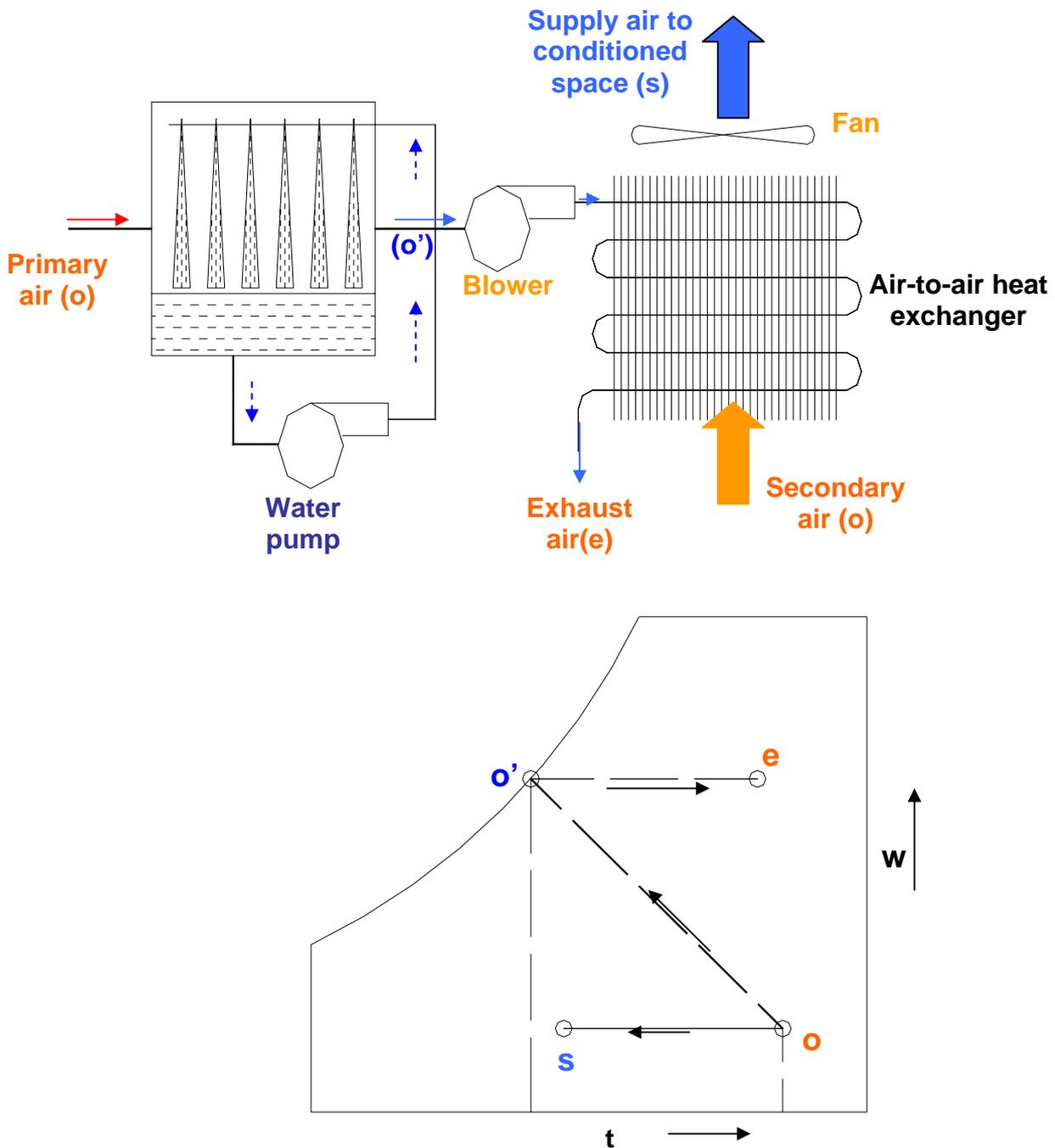


Fig.31.2: An indirect, evaporative cooling system

31.2.3: Multi-stage evaporative cooling systems:

Several modifications are possible which improve efficiency of the evaporative cooling systems significantly. One simple improvement is to sensibly cool the outdoor air before sending it to the evaporative cooler by exchanging heat with the exhaust air from the conditioned space. This is possible since the temperature of the outdoor air will be much higher than the

exhaust air. It is also possible to mix outdoor and return air in some proportion so that the temperature at the inlet to the evaporative cooler can be reduced, thereby improving the performance. Several other schemes of increasing complexity have been suggested to get the maximum possible benefit from the evaporative cooling systems. For example, one can use multistage evaporative cooling systems and obtain supply air temperatures lower than the wet bulb temperature of the outdoor air. Thus multistage systems can be used even in locations where the humidity levels are high.

Figure 30.3 shows a typical two-stage evaporative cooling system and the process on a psychrometric chart. As shown in the figure, in the first stage the primary air cooled and humidified ($o-o'$) due to direct contact with a wet surface cools the secondary air sensibly ($o-1$) in a heat exchanger. In the second stage, the secondary air stream is further cooled by a direct evaporation process ($1-2$). Thus in an ideal case, the final exit temperature of the supply air (t_2) is several degrees lower than the wet bulb temperature of the inlet air to the system (t_o).

31.3. Advantages and disadvantages of evaporative cooling systems:

Compared to the conventional refrigeration based air conditioning systems, the evaporative cooling systems offer the following advantages:

1. Lower equipment and installation costs
2. Substantially lower operating and power costs. Energy savings can be as high as 75 %
3. Ease of fabrication and installation
4. Lower maintenance costs
5. Ensures a very good ventilation due to the large air flow rates involved, hence, are very good especially in 100 % outdoor air applications
6. Better air distribution in the conditioned space due to higher flow rates
7. The fans/blowers create positive pressures in the conditioned space, so that infiltration of outside air is prevented
8. Very environment friendly as no harmful chemicals are used

Compared to the conventional systems, the evaporative cooling systems suffer from the following disadvantages:

1. The moisture level in the conditioned space could be higher, hence, direct evaporative coolers are not good when low humidity levels in the conditioned space is required. However, the indirect evaporative cooler can be used without increasing humidity
2. Since the required air flow rates are much larger, this may create draft and/or high noise levels in the conditioned space
3. Precise control of temperature and humidity in the conditioned space is not possible
4. May lead to health problems due to micro-organisms if the water used is not clean or the wetted surfaces are not maintained properly.

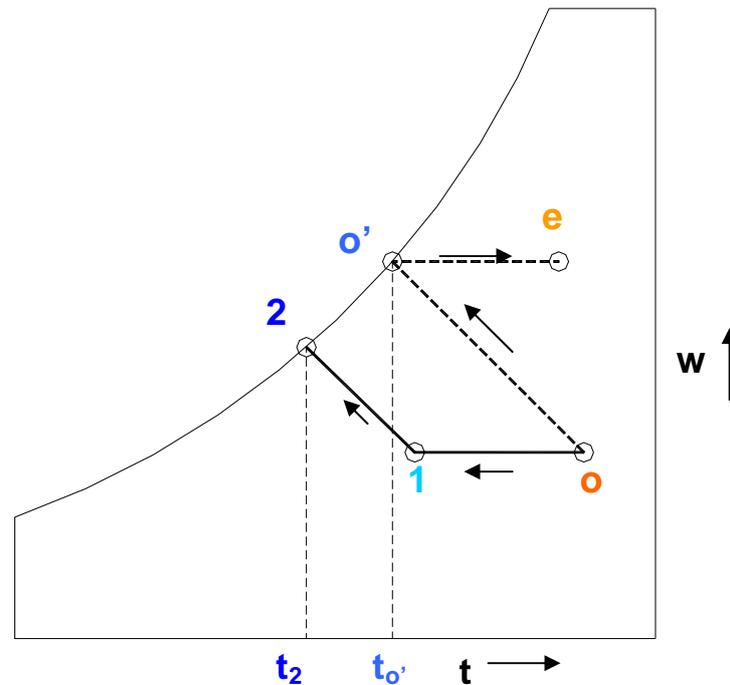
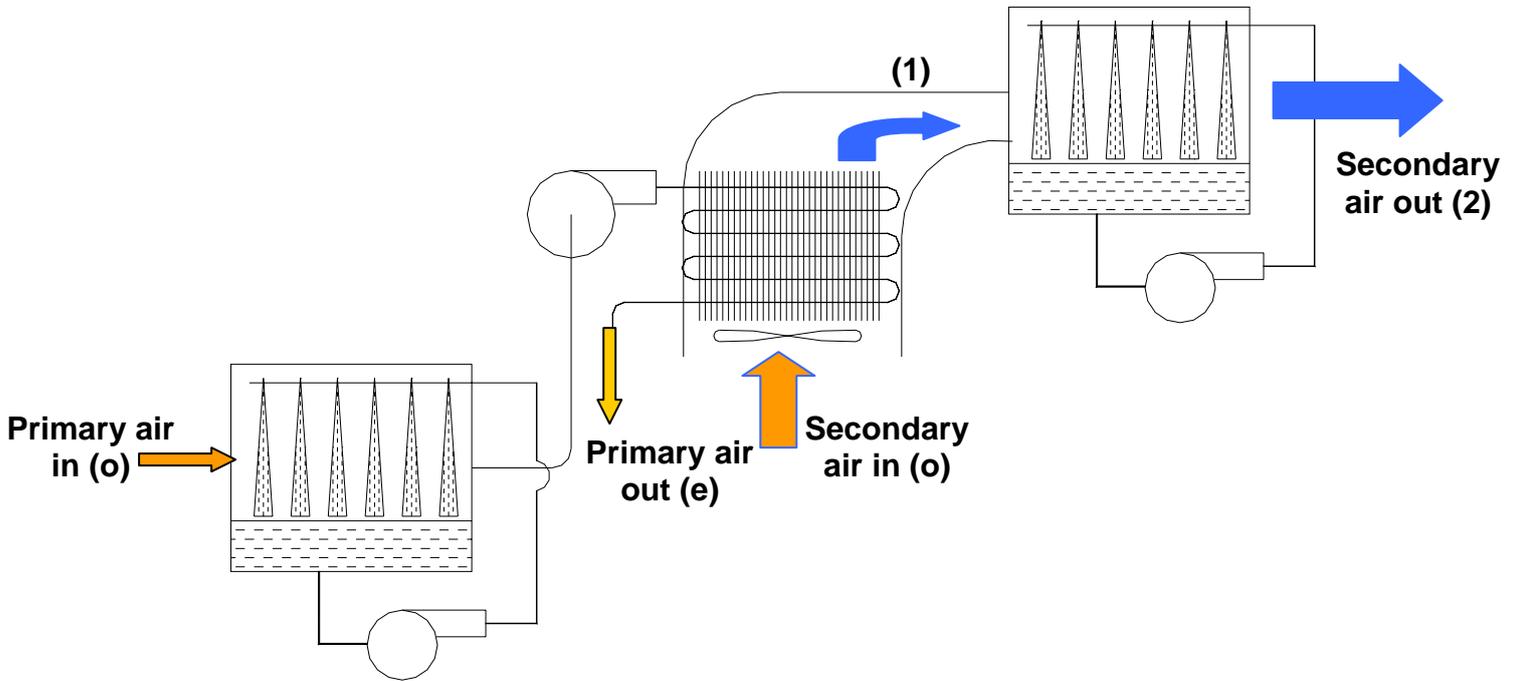


Fig.31.3: A two-stage evaporative cooling system

31.4. Applicability of evaporative cooling systems:

As mentioned before, evaporative cooling systems are ideal in hot and dry places, i.e., in places where the dry bulb temperature is high and the coincident wet bulb temperature is low. However, there are no clear-cut rules as to where these systems can or cannot be used. Evaporative cooling can provide some measure of comfort in any location. However, in many locations where the humidity levels are very high, stand-alone evaporative cooling systems cannot be used for providing thermal comfort especially in residences, office buildings etc. One of the older rules-of-thumb used in USA

specifies that evaporative cooling systems can be used wherever the **average noon relative humidity during July is less than 40%**. However, experience shows that evaporative coolers can be used even in locations where the relative humidity is higher than 40%. A more recent guideline suggests that evaporative cooling can be used in locations where the **summer design wet bulb temperatures are less than about 24°C (75°F)**. It is generally observed that evaporative coolers can compete with conventional systems when the noon relative humidity during July is less than 40%, hence should definitely be considered as a viable alternative, whereas these systems can be used in places where the noon relative humidity is higher than 40% but the design WBT is lower than 24°C, with a greater sacrifice of comfort. It should be mentioned that both these guidelines have been developed for direct evaporative cooling systems. Indirect evaporative coolers can be used over a slightly broader range. Evaporative air conditioning systems can also be used over a broader range of outdoor conditions in factories, industries and commercial buildings, where the comfort criteria is not so rigid (temperatures as high as 30°C in the conditioned space are acceptable). Evaporative air conditioning systems are highly suitable in applications requiring large amounts of ventilation and/or high humidity in the conditioned space such as textile mills, foundries, dry cleaning plants etc.

Evaporative cooling can be combined with a conventional refrigeration based air conditioning systems leading to substantial savings in energy consumption, if the outside conditions are favorable. Again, a number of possibilities exist. For example, the outdoor air can be first cooled in an evaporative cooler and then mixed with the re-circulating air from the conditioned space and then cooled further in the conventional refrigerant or chilled water coil.

31.5. Winter Air Conditioning Systems

In winter the outside conditions are cold and dry. As a result, there will be a continuous transfer of sensible heat as well as moisture (latent heat) from the buildings to the outside. Hence, in order to maintain required comfort conditions in the occupied space an air conditioning system is required which can offset the sensible and latent heat losses from the building. Air supplied to the conditioned space is heated and humidified in the winter air conditioning system to the required level of temperature and moisture content depending upon the sensible and latent heat losses from the building. In winter the heat losses from the conditioned space are partially offset by solar and internal heat gains. Thus in a conservative design of winter A/C systems, the effects of solar radiation and internal heat gain are not considered.

Heating and humidification of air can be achieved by different schemes. Figure 31.4 shows one such scheme along with the cycle on psychrometric chart. As shown in the figure, the mixed air (mixture of return and outdoor air) is first pre-heated (**m-1**) in the pre-heater, then humidified using a humidifier or an air washer (**1-2**) and then finally reheated in the re-heater (**2-s**). The reheated air at state 's' is supplied to the conditioned space.

The flow rate of supply air should be such that when released into the conditioned space at state 's', it should be able to maintain the conditioned

space at state I and offset the sensible and latent heat losses (Q_s and Q_l). Pre-heating of air is advantageous as it ensures that water in the humidifier/air washer does not freeze. In addition, by controlling the heat supplied in the pre-heater one can control the moisture content in the conditioned space.

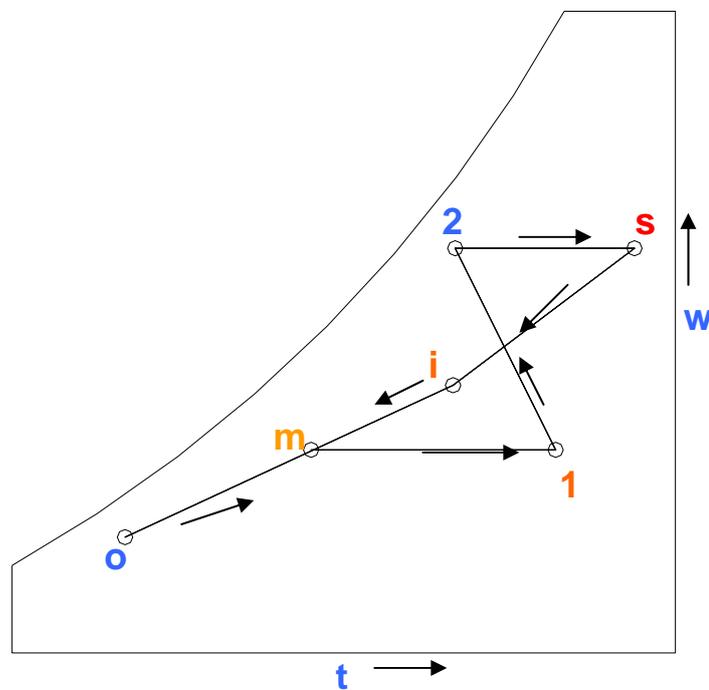
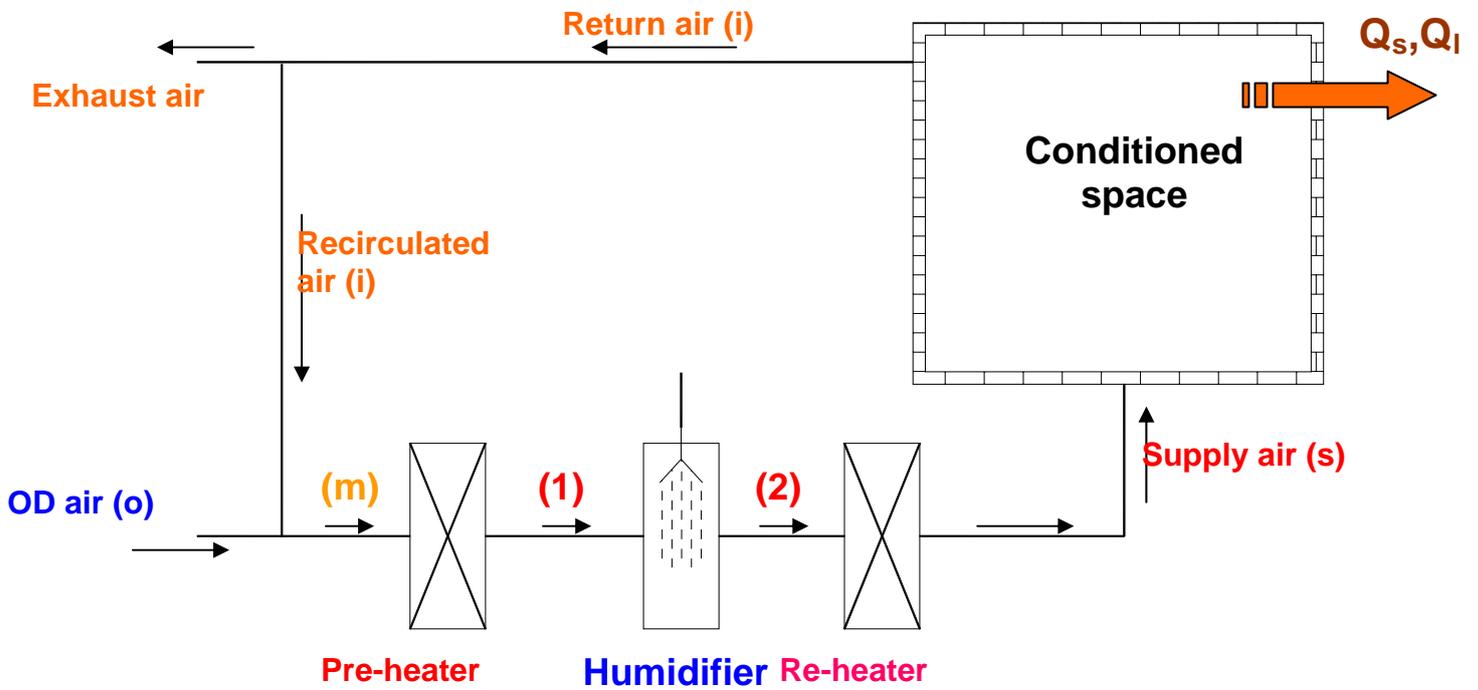


Fig.31.4: A winter air conditioning system with a pre-heater

The humidification of air can be achieved in several ways, e.g. by bringing the air in contact with a wetted surface, or with droplets of water as in an air washer, by adding aerosol sized water droplets directly to air or by direct addition of dry saturated or superheated steam. Humidification by direct contact with a wetted surface or by using an air washer are not recommended for comfort applications or for other applications where people are present in the conditioned space due to potential health hazards by the presence of micro-organisms in water. The most common method of humidifying air for these applications is by direct addition of dry steam to air. When air is humidified by contact with wetted surface as in an air washer, then temperature of air decreases as its humidity increases due to simultaneous transfer of sensible and latent heat. If the air washer functions as an adiabatic saturator, then humidification proceeds along the constant wet bulb temperature line. However, **when air is humidified by directly adding dry, saturated steam, then the humidification proceeds close to the constant dry bulb temperature line.** The final state of air is always obtained by applying conservation of mass (water) and conservation of energy equations to the humidification process.

By applying energy balance across the conditioned space, at steady state, the sensible and latent heat losses from the building can be written as:

$$Q_s = \dot{m}_s c_{pm}(t_s - t_i) \quad (31.3)$$

$$Q_l = \dot{m}_s h_{fg}(w_s - w_i) \quad (31.4)$$

where \dot{m}_s is the mass flow rate of supply air, c_{pm} is the specific heat of air, h_{fg} is the latent heat of vapourization of water, w_s and w_i are the supply and return air humidity ratios and t_s , t_i are the supply and return temperatures of air. By applying mass and/or energy balance equations across individual components, the amount of sensible heat transfer rate to the pre-heater and re-heater and the amount of moisture to be added in the humidifier can easily be calculated.

Figure 31.5 shows another scheme that can also be used for heating and humidification of air as required in a winter air conditioning system. As shown in the figure, this system does not consist of a pre-heater. The mixed air is directly humidified using an air washer (**m-1**) and is then reheated (**1-s**) before supplying it to the conditioned space. Though this system is simpler compared to the previous one, it suffers from disadvantages such as possibility of water freezing in the air washer when large amount of cold outdoor air is used and also from health hazards to the occupants if the water used in the air washer is not clean. Hence this system is not recommended for comfort conditioning but can be used in applications where the air temperatures at the inlet to the air washer are above 0°C and the conditioned space is used for products or processes, but not for providing personnel comfort.

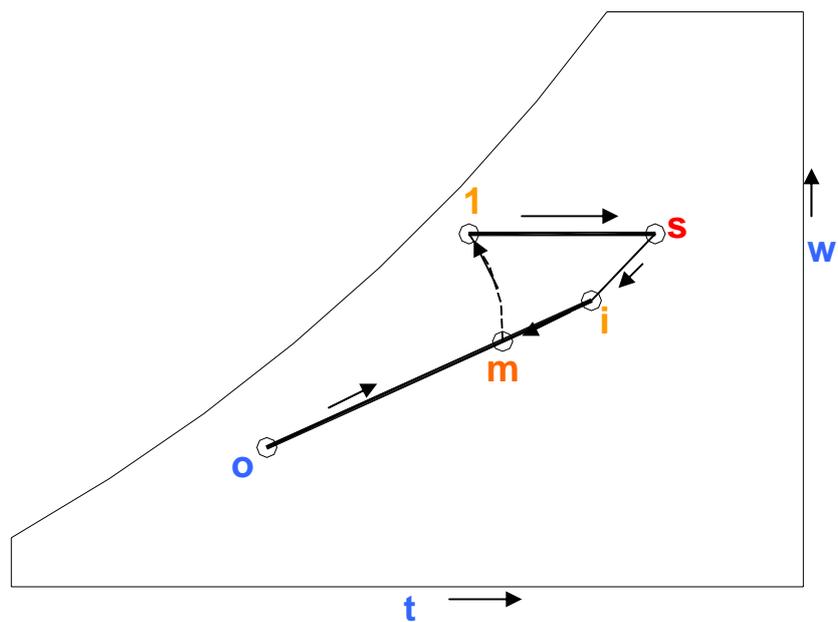
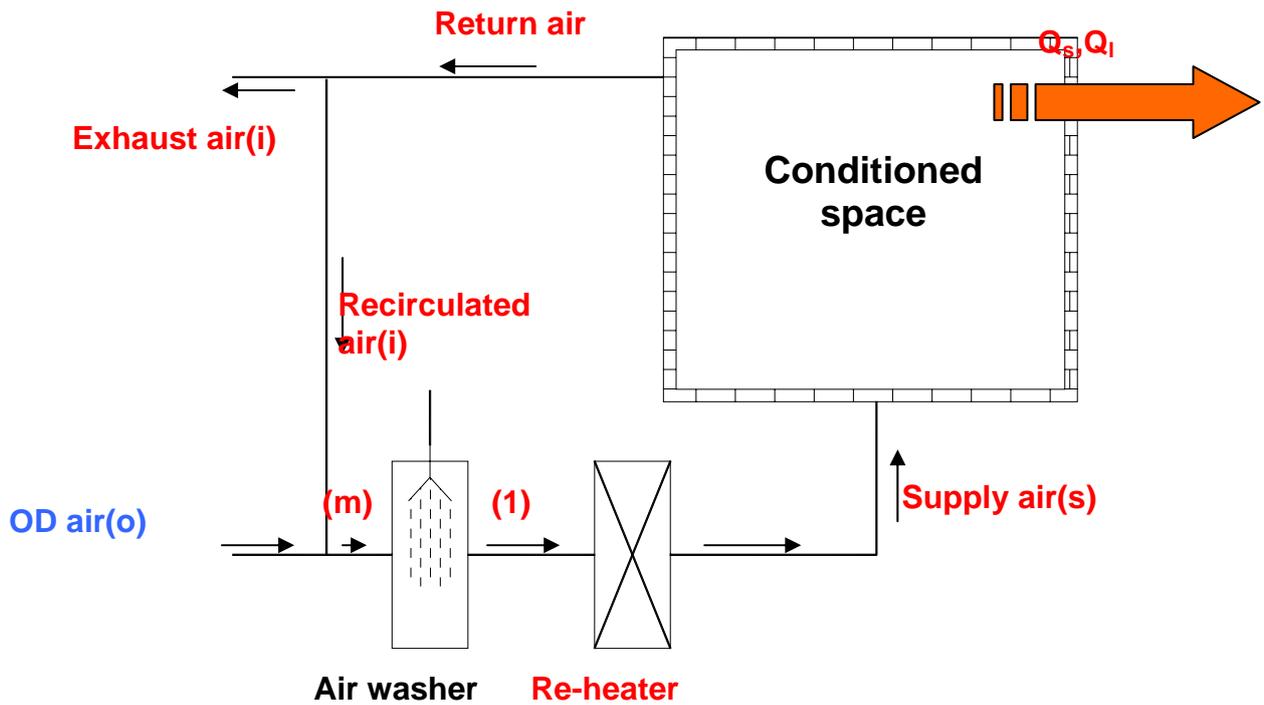


Fig.31.5: A winter air conditioning system without a pre-heater

Actual winter air conditioning systems, in addition to the basic components shown above, consist of fans or blowers for air circulation and filters for purifying air. The fan or blower introduces sensible heat into the air stream as all the electrical power input to the fan is finally dissipated in the form of heat.

31.6. All year (complete) air conditioning systems:

Figure 30.6 shows a complete air conditioning system that can be used for providing air conditioning throughout the year, i.e., during summer as well as winter. As shown in the figure, the system consists of a filter, a heating coil, a cooling & dehumidifying coil, a re-heating coil, a humidifier and a blower. In addition to these, actual systems consist of several other accessories such as dampers for controlling flow rates of re-circulated and outdoor (OD) air, control systems for controlling the space conditions, safety devices etc. Large air conditioning systems use blowers in the return air stream also. Generally, during summer the heating and humidifying coils remain inactive, while during winter the cooling and dehumidifying coil remains inactive. However, in some applications for precise control of conditions in the conditioned space all the coils may have to be made active. The blowers will remain active throughout the year, as air has to be circulated during summer as well as during winter. When the outdoor conditions are favourable, it is possible to maintain comfort conditions by using filtered outdoor air alone, in which case only the blowers will be running and all the coils will be inactive leading to significant savings in energy consumption. A control system is required which changes-over the system from winter operation to summer operation or vice versa depending upon the outdoor conditions.

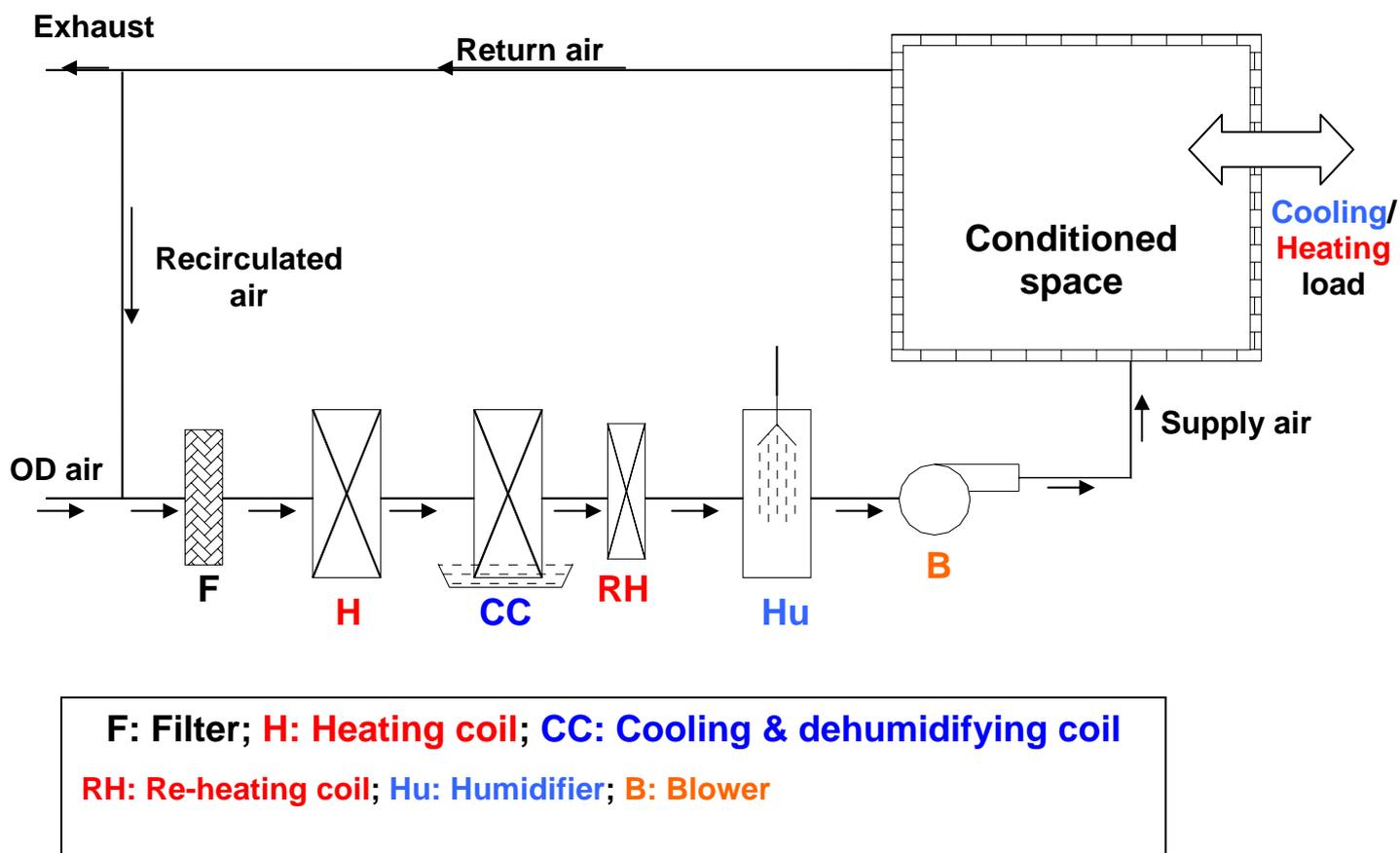


Fig.31.6: An all year air conditioning system

Questions and answers:

1. Which of the following statements are TRUE?

- a) Evaporative cooling systems are attractive for hot and humid climates
- b) Evaporative cooling systems are attractive for hot and dry climates
- c) Evaporative cooling systems are ideal for comfort applications
- d) Evaporative cooling systems are ideal for several industrial applications

Ans.: b) and d)

2. Which of the following statements are TRUE?

- a) In a direct evaporative cooling system, the lowest possible temperature is the wet bulb temperature corresponding to the outdoor air
- b) In a direct evaporative cooling system, the lowest possible temperature is the dew point temperature corresponding to the outdoor air
- c) In a direct evaporative cooling system, cooled and humidified air is supplied to the conditioned space
- d) In a direct evaporative cooling system, cooled and dehumidified air is supplied to the conditioned space

Ans.: a) and c)

3. Which of the following statements are TRUE?

- a) In an indirect evaporative cooling system, the air supplied to the conditioned space is at a lower temperature, but higher humidity ratio
- b) In an indirect evaporative cooling system, the air supplied to the conditioned space is at a lower temperature and at a humidity ratio corresponding to the outdoor air
- c) Compared to direct evaporative cooling systems, it is possible to achieve lower supply air temperatures in simple indirect evaporative coolers
- d) In multi-stage evaporative cooling systems, it is possible to cool the air to a temperature lower than the entering air WBT

Ans.: b) and d)

4. Which of the following statements are TRUE?

- a) Evaporative cooling systems are environment friendly
- b) Evaporative cooling systems offer lower initial and lower running costs
- c) Evaporative cooling systems are easier to maintain and fabricate
- d) Evaporative systems provide better control on indoor climate

Ans.: a), b) and c)

5. Which of the following statements are TRUE?

- a) Direct evaporative cooling systems are attractive in places where the summer design WBT is greater than 24°C
- b) Direct evaporative cooling systems are attractive in places where the summer design WBT is less than 24°C
- c) Indirect evaporative cooling systems can be used over an extended range of climatic conditions
- d) A combination of evaporative cooling system with conventional air conditioning system can offer better overall performance

Ans.: b), c) and d)

6. Which of the following statements are TRUE?

- a) In winter air conditioning systems, heated and dehumidified air is supplied to the conditioned space
- b) In winter air conditioning systems, heated and humidified air is supplied to the conditioned space
- c) A pre-heater is recommended in winter air conditioning systems to improve overall efficiency of the system
- d) A pre-heater is recommended in winter air conditioning systems to prevent freezing of water in the humidifier and for better control

Ans.: b) and d)

7. Which of the following statements are TRUE?

- a) When humidification is done using an air washer, the temperature of air drops during humidification
- b) When humidification is done using an air washer, the temperature of air rises during humidification
- c) When humidification is carried out by adding dry steam, the temperature of air remains close to the WBT of entering air
- d) When humidification is carried out by adding dry steam, the temperature of air remains close to the DBT of entering air

Ans.: a) and d)

8. Which of the following statements are TRUE?

- a) An all year air conditioning system can be used either as a summer air conditioning system or as a winter air conditioning system
- b) When an all year air conditioning system is used during summer, the heaters are always switched-off
- c) When an all year air conditioning system is used during winter, the cooling and dehumidification coils are switched-off
- d) In an all year air conditioning systems, the blowers are always on

Ans.: a), c) and d)

9. A large warehouse located at an altitude of 1500 m has to be maintained at a DBT of 27°C and a relative humidity of 50% using a direct evaporative cooling system. The outdoor conditions are 33°C (DBT) and 15°C (WBT). The cooling load on the warehouse is 352 kW. A supply fan located in the downstream of the evaporative cooler adds 15 kW of heat. Find the required mass flow rate of air. Assume the process in evaporative cooler to follow a constant WBT.

Ans.:

At 1500m, the barometric pressure is equal to **84.436 kPa**.

Inlet conditions to the evaporative cooling system are the outdoor conditions:

$$t_o = 33^\circ\text{C}, \text{WBT}_o = 15^\circ\text{C}$$

At these conditions and a barometric pressure of 84.436 kPa, the enthalpy of outdoor air is obtained using psychrometric equations¹ as:

$$h_o = 46.67 \text{ kJ/kgda}$$

The above system is shown on psychrometric chart in Fig.31.6

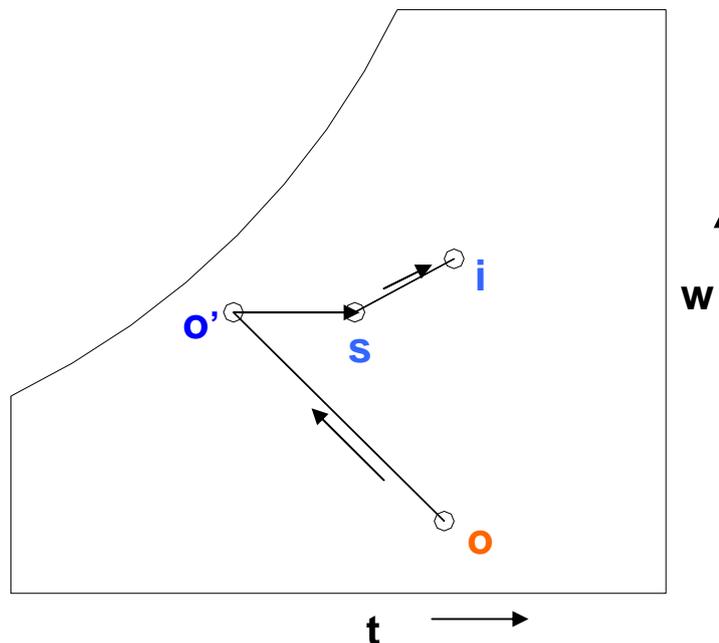


Fig.31.7

Assuming the evaporative process to follow a constant WBT and hence nearly a constant enthalpy line,

$$h_o = h_{o'} = 46.67 \text{ kJ/kgda}$$

¹ Standard psychrometric chart cannot be used here as the barometric pressure is not 1 atm.

Applying energy balance for the sensible heating process in the fan (process o'-s) and heating and humidification process through the conditioned space (process s-i), we obtain:

$$m_s(h_s - h_o) = 15 = \text{sensible heat added due to fan} \quad (\text{E.1})$$

$$m_s(h_i - h_s) = 352 = \text{cooling load on the room} \quad (\text{E.2})$$

From psychrometric equations, for the inside condition of the warehouse (DBT=27°C and RH = 50%), the enthalpy h_i is found from psychrometric equations as:

$$h_i = 61.38 \text{ kJ/kgda}$$

We have two unknowns (m_s and h_s) and two equations (E.1 and E.2), hence solving the equations simultaneously yields:

$$m_s = 24.94 \text{ kJ/kg and } h_s = 47.27 \text{ kJ/kgda} \quad (\text{Ans.})$$

10. A winter air conditioning system maintains a building at 21°C and 40% RH. The outdoor conditions are 0°C (DBT) and 100% RH. The sensible load on the building is 100 kW, while the latent heating load is 25 kW. In the air conditioning system, 50% of the outdoor air (by mass) is mixed with 50% of the room air. The mixed air is heated in a pre-heater to 25°C and then required amount of dry saturated steam at 1 atm. pressure is added to the pre-heated air in a humidifier. The humidified air is then heated to supply temperature of 45°C and is then supplied to the room. Find a) The required mass flow rate of supply air, b) Required amount of steam to be added, and c) Required heat input in pre-heater and re-heater. Barometric pressure = 1atm.

Ans.: From psychrometric chart the following properties are obtained:

Outdoor conditions: 0°C (DBT) and 100% RH

$$W_o = 0.00377 \text{ kgw/kgda, } h_o = 9.439 \text{ kJ/kgda}$$

Indoor conditions: 21°C (DBT) and 40% RH

$$W_i = 0.00617 \text{ kgw/kgda, } h_i = 36.66 \text{ kJ/kgda}$$

Since equal amounts of outdoor and indoor air are mixed:

$$t_m = 10.5^\circ\text{C, } W_m = 0.00497 \text{ kgw/kgda, } h_m = 23.05 \text{ kJ/kgda}$$

From sensible energy balance across the room (Process s-i) in Fig.31.8:

a) Required mass flow rate of supply air is:

$$m_s = Q_s / \{c_{pm}(t_s - t_i)\} = 100 / \{1.0216(45 - 21)\} = 4.08 \text{ kg/s} \quad (\text{Ans.})$$

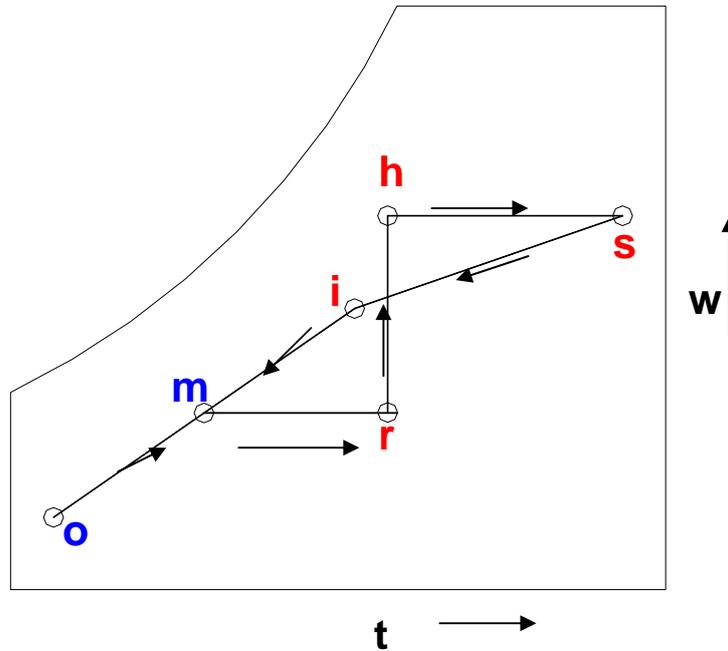


Fig.31.8

From latent energy balance for process s-i, the humidity ratio of supply air is found to be:

$$W_s = W_i + Ql/(h_{fg}.m_s) = 0.00617 + 25/(2501 \times 4.08) = 0.00862 \text{ kgw/kgda}$$

b) Required amount of steam to be added m_w is obtained from mass balance across the humidifier (process r-h) as:

$$m_w = m_s(W_s - W_m) = 4.08 \times (0.00862 - 0.00497) = 0.0149 \text{ kg/s} \quad (\text{Ans.})$$

c) Heat input to the pre-heater (process m-r) is obtained as:

$$Q_{ph} = m_s.c_{pm}(t_r - t_m) = 60.44 \text{ kW} \quad (\text{Ans.})$$

Heat input to the re-heater (process h-s) is obtained as:

$$Q_{rh} = m_s.c_{pm}(t_s - t_r) = 83.36 \text{ kW} \quad (\text{Ans.})$$

In the above example, it is assumed that during addition of steam, the dry bulb temperature of air remains constant. A simple check by using energy balance across the humidifier shows that this assumption is valid.