Chapter 6

Refrigeration and Air Conditioning

CHAPTER HIGHLIGHTS

- Psychromtry
- Specific Humidity and Relative Humidity
- Dry Bulb Temperature
- Dew Point Temperature (DPT) or T_{dp}
- Adiabatic Saturation
- Wet Bulb Temperature (T_{wb} or WBT)
- Psychrometric Chart
- Air Conditioning Processes
- Heating and Humidification
- Cooling with Dehumidification
- Winter Air Conditioning Process
- Bye-pass Factor (BPF)
- Refrigeration and Air Conditioning
- Classification of Refrigerants
- Designation of Refrigerants
- Refrigeration Cycles
- Bell Coleman Cycle or Reversed Brayton Cycle or Reversed Joule Cycle

Psychrometry

Introduction

- Air conditioning is the simultaneous control of temperature, humidity, air velocity and purity of air. It is a branch of science which deals with the study of properties of moist air.
- Atmospheric air consists of dry air and water vapour.

Moist air = Dry air + Water vapour

- Dry air is the fixed part consists of N_2, O_2, CO_2 and inert gases, and water vapour is the variable part.
- Water vapour in the air exists at low pressure and hence it be treated as ideal gas.
- Total atmosphere pressure, $P_t = P_v + P_a$

where P_v and P_a are partial vapour pressure of dry air and water vapour.

$P_v V_v = m_v R_v T_v$ and $P_a V_a = m_a R_a T_a$

Now, $V_a = V_v$ and $T_v = T_a$

$$\therefore \frac{P_v}{P_a} = \frac{m_v R_v}{m_a R_a} \Rightarrow \frac{m_v}{m_a} = \frac{P_v}{P_a} \cdot \frac{R_a}{R_v}$$

Basic Definitions

Specific Humidity and Relative Humidity

(a) Specific humidity (absolute humidity or humidity ratio)

Specific humidity is the mass of water vapour present in a unit mass of dry air.

Specific humidity,

$$\boxed{W = \frac{M_v}{M_a}} \frac{\text{kg water vapour}}{\text{kg dry air}}$$

It can also be expressed as

$$\boxed{W = 0.622 \frac{P_v}{P_a} = 0.622 \frac{P_v}{P - P_v}}$$

$$\therefore \quad P = P_V + P_a$$

where P = total pressure

(b) Relative humidity

It is the ratio of the amount of moisture the air holds (M_v) relative to the maximum amount of moisture the air can hold at the same temperature (M_g). It can be represented as

$$\boxed{\phi = \frac{M_v}{M_g} = \frac{P_v}{P_{\text{sat}}}}$$

Useful tip: If we take 1 kg of dry air, by definition we can say that dry air contains no water vapour and thus its specific humidity is zero. Now, let us add some water vapour to this dry air. Then, the specific humidity will increase. As more vapour or moisture is added, the specific humidity will keep increasing until the air can hold no more moisture. At this point, the air is said to be saturated with moisture and it is called saturated air.

Any moisture introduced into saturated air will result into the condensation.

Relation Between Specific Humidity (ω) and Relative Humidity (ϕ)

$$\phi = \frac{\omega P}{(0.622 + \omega)P_{sat}}$$

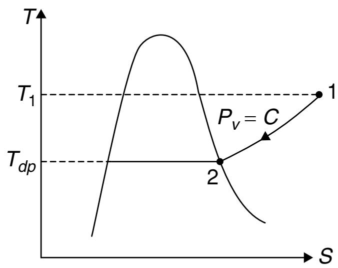
where ω = humidity ratio

Useful tip For saturated air, relative humidity is 1 or 100% and for dry air, relative humidity is zero. Temperature is the parameter on which the amount of moisture air can hold depends. Therefore, even when specific humidity remains constant, the relative humidity varies with temperature.

Dry bulb temperature (T_d) The ordinary temperature of atmospheric air is frequently referred to as dry bulb temperature.

Dew point temperature (DPT) or T_{dp} The dew point temperature, T_{dp}, is defined as the temperature at which condensation begins when the air is cooled at constant pressure. In other words T_{dp} is the saturation temperature of water corresponding to the vapour pressure.

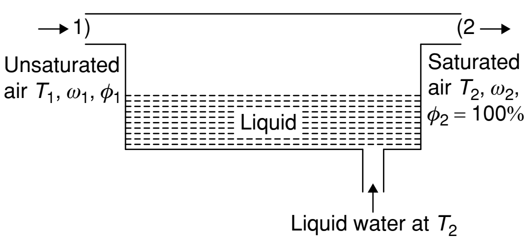
$T_{dp} = T_{sat@p}$



Significance: When we buy a cold canned drink from a vending machine on a hot and humid day, dew forms on the can. The formation of dew on the can indicates that the temperature of the drink is less than the dew point temperature of the surrounding air.

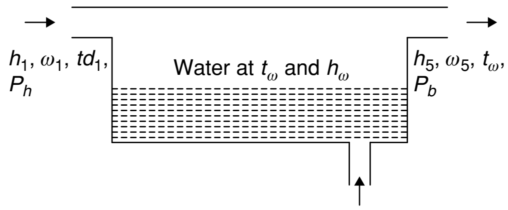
Adiabatic saturation: It is a way of determining the relative humidity or specific humidity.

Consider the steady flow of an unsaturated air water vapour mixture through an insulated device called adiabatic saturator. Assume that equilibrium is attained between the water and air-water vapour mixture in the device and hence saturated air-water vapour leaves the device.



If make up water is supplied to the channel at the rate of evaporation at temperature T_2, the adiabatic saturation process can be considered as a steady flow process.

Let h_1 be the enthalpy, ω_1 the specific humidity, td_1 the dry bulb temperature and P_b the total pressure at the inlet and the corresponding value at the outlet be h_5, ω_5, t_ω and P_b.



$$h_1 + (\omega_5 - \omega_1)\, h_\omega = h_5$$

where h_ω is the enthalpy of water supplied, t_ω is the thermodynamic wet bulb temperature.

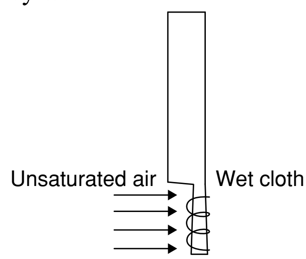
$$h_1 - \omega_1 h_\omega = h_5 - \omega_5\, h_\omega$$

This is known as sigma function.

Measuring the temperature and pressure at the inlet and exit of the adiabatic saturator the specific humidity can be determined.

Wet bulb temperature (T_{wb} or WBT)

It is the temperature measured by the thermometer whose bulb is covered by wet cloth.



Air takes moisture and hence temperature drops due to latent heat of vapourization. The temperature measured in WBT.

WBT is an indication of moisture content in air. If the difference between DBT and WBT is large, then it means the moisture content in air is less. This is because if the moisture content in the air is less then it will absorb more vapour and as it absorbs more vapour, it takes away more heat and hence its temperature drops and thereby WBT will be low.

Wet bulb depression = DBT – WBT

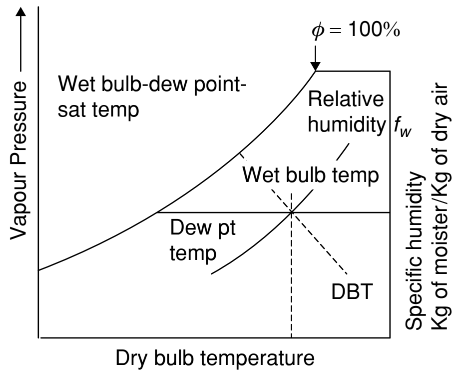
NOTE

For saturated vapour, wet bulb depression is zero because at saturation condition, DBT = WBT.

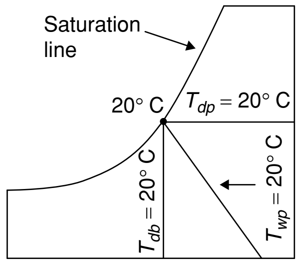
Psychrometric Chart

- Psychrometric chart is a graphical representation of solution of the adiabatic saturation.
- A psychrometer is an instrument used to measure the wet bulb and dry bulb temperature of an air-water vapour mixture. This works on the principle of adiabatic saturation.

- Sling psychrometer is an instrument used to record dry bulb temperature and wet bulb temperatures simultaneously.



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



Application of Psychrometry

In the field of air conditioning the various processes used are heating, cooling, humidification and adiabatic mixing of air-water vapour. These processes can be easily analyzed with the help of a psychrometric chart.

Air Conditioning Processes

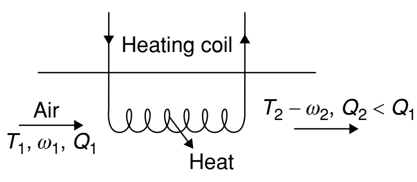
The air conditioning processes include

(a) Simple heating (raising the temperature)
(b) Simple cooling (lowering temperature)
(c) Humidifying (adding moisture)
(d) Dehumidifying (removing moisture)

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

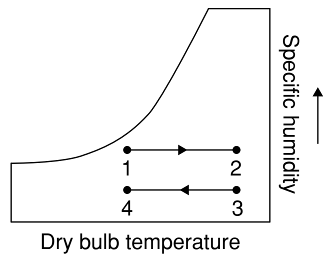
Air is commonly heated and humidified in winter and cooled and dehumidified in summer.

(a) Sensible heating and sensible cooling



In simple heating 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 above. 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 process. Such a heating proceeds in the direction of increasing dry bulb temperature.

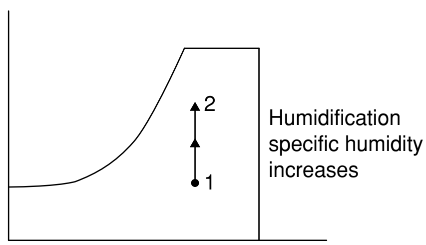
Useful tip The relative humidity of air decreases during a heating process even if the specific humidity ω remains constant. This is because the relative humidity is the ratio of the moisture content to the moisture capacity of the air at the same temperature and moisture capacity of air increases with increase in temperature.



1–2 → Sensible heating
3–4 → Sensible cooling

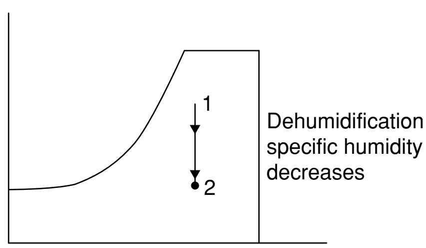
(b) Humidification

Humidification is a process in which moisture is added at constant temperature.



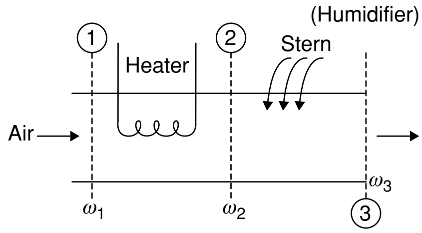
(c) Dehumidification

Dehumidification is a process in which moisture is removed at constant temperature.



Heating and humidification

Problem associated with sensible heating is that it reduces the relative humidity and this can be eliminated by spraying steam in the heated air.

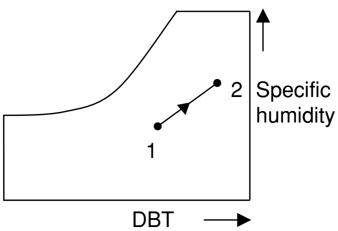


1 – 2 → Sensible heating
2 – 3 → Humidification
Specific humidity, $\omega_1 = \omega_2$ and $\omega_3 > \omega_2$

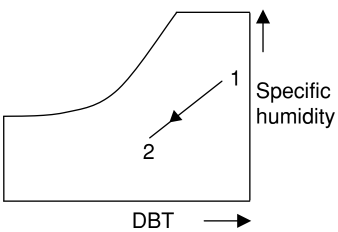
Useful tip If steam is introduced in the humidification section, this will result in humidification with additional heating ($T_3 > T_2$).

If humidification is accomplished by spraying water into the air stream, part of the latent heat of vapourization come from air, which results in the cooling of the heated air stream ($T_3 > T_2$). Air should be heated to a higher temperature in the heating section in this case to make up for the cooling effect during the humidification process.

This process can be shown in the psychrometric chart as:



(e) Cooling with dehumidification
This process is generally followed in summer air conditioning. After sensible cooling the air, the relative humidity increases and to reduce the humidity or moisture content from the air, the air has to dehumidify. This needs cooling of air below the dew point temperature.



Evaporative Cooling

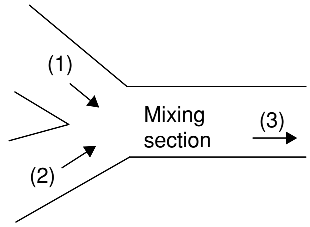
It is based on a simple principle. As water evaporates, the latent heat of vapourization is absorbed from the water body and the surrounding air. As a result, both the water and the air are cooled during the process.

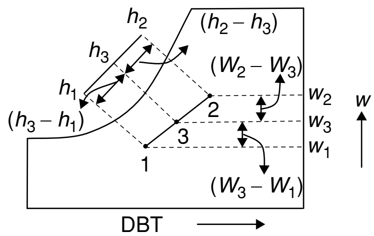
Useful tip The evaporative cooling is identical to the adiabatic saturation process since the heat transfer between the air stream and the surroundings is usually negligible. Therefore the evaporative cooling process follows a line of constant wet bulb temperature on the psychrometric chart.

Also the constant wet bulb temperature lines almost coincide with the constant enthalpy lines.

$$\therefore \quad T_{wb} = \text{Constant}$$
$$h = \text{Constant}$$

Adiabatic Mixing of Two Air Streams





The air stream consists of dry air as well as water vapour. Mass and energy balance for the adiabatic mixing can be given as

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

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

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

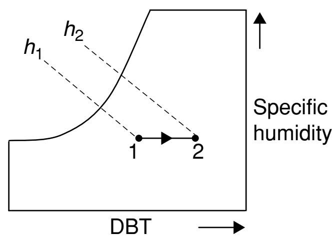
Eliminating $\dot{M}_{a_3}$ from the above relations, we get

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

We can conclude that when two air streams at two different states(1 and 2) are mixed adiabatically, the state of the mixture (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 $\dot{M}_{a_1}$ and $\dot{M}_{a_2}$.

Sensible Heat Load (SHL)

Sensible heating process represents sensible heat load.



$$\text{SHL}(KW) = \dot{M}_a(\text{Kg/s})(h_2 - h_1)\ \text{KJ/Kg} = \dot{M}_a C_{\text{phs}}(t_2 - t_1)$$

where C_{phs} represents the humid specific heat = 1.0216 KJ/Kg of dry air

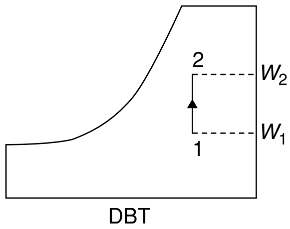
$$\text{SHL} = \dot{M}_a C_{\text{phs}} \Delta T$$

$$= \left(\frac{\dot{V}}{60} \cdot \rho\right) C_{\text{phs}} (\Delta T)_{\text{air}}$$

where $\dot{V}$ is the volume flow rate of air in cubic meter per minute.

$$\text{SHL} = \left(\frac{\dot{V}}{60} \times 1.2\right) \times 1.0216 \times \Delta T = 0.0204\ \dot{V}\ \Delta T\ KW.$$

Latent Heat Load (LHL)



Humidification process represents latent heat load.

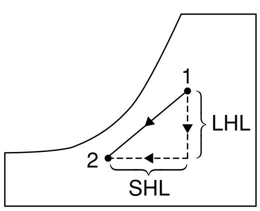
$$\text{LHL}(KW) = \dot{M}_a (W_2 - W_1) h_{fg}$$

$$= \left(\frac{\dot{V}}{60} \rho\right) \Delta W h_{fg} KW,\ h_{fg} \text{ being the specific latent heat}$$

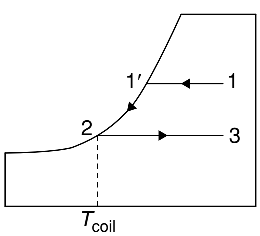
Useful tip: Total heat load, THL = SHL + LHL
Also sensible heat factor,

$$\text{SHF} = \frac{\text{SHL}}{\text{THL}}$$

$$= \frac{\text{SHL}}{\text{SHL} + \text{LHL}}$$



Ideal summer air conditioning



- Summer air conditioning is actually cooling and dehumidification process.
- It consists of the following processes

(a) Sensible cooling (1 – 1′)
(b) Dehumidification (1′ – 2)

The temperature at state 2 is very low. Therefore, sensible heating is done at this stage so that state 2 is a controllable temperature.

- The energy equation for this process can be written as:

1–2 (cooling load)

$$\dot{M}_{a_1} h_1 - \dot{Q} = \dot{M}_a h_2 + \dot{M}_f h_{f_2} = \dot{M}_a h_2 + \dot{M}_a (W_1 - W_2) h_{f_2}$$

$$\Rightarrow \dot{Q} = \dot{M}_a (h_1 - h_2) - \dot{M}_a (W_1 - W_2) h_{f_2}\ \text{kW}$$

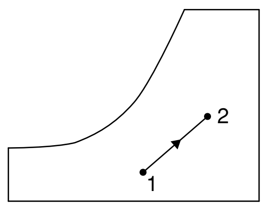
2–3 (sensible heat load)

$$\dot{M}_a h_2 + \dot{Q} + \dot{M}_a h_3$$

$$\dot{Q} = \dot{M}_a (h_3 - h_2)\ \text{kW}$$

Winter air conditioning process

- Winter air conditioning is actually heating and humidification.



- The energy equation for this process can be written as-

$$\dot{M}_a h_1 + \dot{M}_f h_{f_2} + \dot{Q} = \dot{M}_a h_2$$

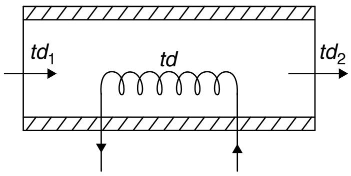
$$\Rightarrow \dot{M}_a h_1 + \dot{M}_a (W_2 - W_1) h_{f_2} + \dot{Q} = \dot{M}_a h_2$$

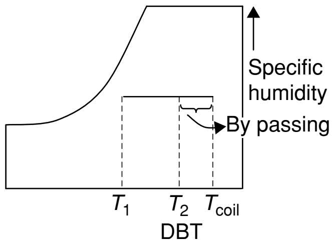
$$\Rightarrow \dot{Q} = \dot{M}_a (h_2 - h_1) + \dot{M}_a (W_1 - W_2) h_{f_2}$$

Bypass Factor (BPF)

Let *td* be the temperature of the heating coil. In ideal case, on entering the heating coil, air at temperature *td*, must be able to leave the coil at temperature *td*. But in actual practice the air can leave only with temperature td_2. This is due to the inefficiencies of the heating system. This inefficiency is expressed as bypass factor, denoted by BPF.

Bypass factor, $\text{BPF} = \dfrac{td - td_2}{td - td_1}$,





Useful tip: BPF signifies the inefficiency of the system

Contact factor = 1 – BPF

Refrigeration and Air Conditioning

Refrigeration

It is defined as the process by which the temperature of a given space or a substance is lowered below that of the atmosphere or surroundings.

- Production of low temperature is achieved by following processes:

1. Throttling expansion of a liquid with flashing
2. Reversible adiabatic expansion of a gas
3. Irreversible adiabatic expansion of a real gas
4. Thermoelectric cooling
5. Adiabatic demagnetization

Air Conditioning

- Air conditioning is the process of altering the properties of air such as temperature, humidity, air movement and circulation to more favourable conditions.
- Air conditioning can refer to any from of technological cooling or heating that modifies the condition of air.
- Comfort conditions:

Temperature	:	22.8°C to 25°C
Humidity	:	35% to 60%
Air circulation	:	5 m/min to 8 m/min

Tonne of Refrigeration

It is defined as the amount of heat removed from 2000 pounds of water at 32°F = to convert into ice at 32°F in 24 hours.

OR

It is defined as the amount of heat removed from 1000 kg of water at 0°C to convert into ice at 0°C in 24 hours.

$$\therefore \quad 1 \text{ tonne of refrigeration } = \frac{1000 \times 336}{24 \times 60}$$

$$= 233 \text{ kJ/min}$$

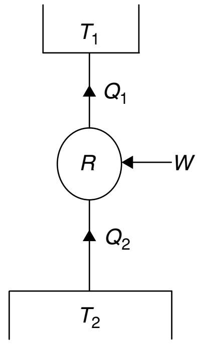
$\approx$ 210 kJ/min

$= 3.52$ kW

- A machine which has the capacity of producing a cooling effect of 210 kJ/min is designed as 1 ton machine.

Refrigerator

If the heat engine operates in reverse direction used for cooling purpose is called as refrigerator.



- $(\text{COP})_R = \dfrac{\text{Desired effect}}{W}$

$$= \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

- $(\text{COP})_{HP} = 1 + (\text{COP})_R$
- Energy performance ratio (EPR) = $1 + (\text{COP})_R$
- Heat rejection ratio $(\text{HRR}) = 1 + \dfrac{1}{(\text{COP})_R}$
- Horse power per tonne of refrigeration $\left(\dfrac{\text{HP}}{\text{TR}}\right) = \dfrac{4.71}{(\text{COP})_R}$

Types of Refrigeration Systems

(a) Dry ice refrigeration

- Solid CO_2 is called dry ice.
- Changes from solid state to vapour state without converting in to liquid state.
- Evaporation (OR) sublimation temperature of dry ice at atmospheric pressure is –78°C.

Application:

Dry ice is used to preserve food stuff during transportation.

(b) Evaporation refrigeration

- Evaporation cooling is adiabatic transfer of heat from air to water.

Application:

(i) Used in desert coolers or room coolers.

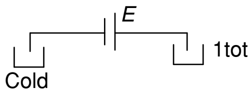
(ii) Used in making artificial snow.

(c) Liquid gas refrigeration

- Refrigerants: Liquid nitrogen, liquid CO_2
- Refrigerants should be nontoxic in nature.

Application: Used for cooling the vehicles transporting food stuff.

(d) Thermoelectric refrigeration

- Employs Peltier effect.
- 

- Antimony (Sb), Bismuth (Be) metals are commonly used.

(e) Steam jet refrigeration

Principle: Boiling point of water can be reduced by reducing the pressure.

Classification of Refrigerants

Primary refrigerants: Take part directly in the refrigerating systems.

Secondary Refrigerants: Are first cooled by primary refrigerants and then used for cooling purpose.

Primary refrigerants	Secondary refrigerants
NH_3, CO_2, SO_2, methyl chlorides, methylene chloride, Freon group, ammonia	Air Water Brine (salt solution of water)

Designation of Refrigerants

Case (1): Refrigerant is a saturated hydro carbon.

- General formula is $CmHnFpClq$
- Refrigerant is designated as $R(m-1)\ (n+1)P$

  where $n + p + q = 2m + 2$

Example 1: Write the chemical formula of R_{11}.

$R_{11} = R_{011} = R(m-1)\ (n+1)_P$

$M - 1 = 0 \quad | \quad n + 1 = 1 \quad p = 1$

$M = 1 \quad n = 0$

$N + p + q = 2m + 2$

$\Rightarrow 0 + 1 + q = 2(1) + 2$

$\Rightarrow q = 3$

$\therefore C_m\, H_n\, F_p\, Cl_q \rightarrow C_1\, H_0\, F_1\, Cl_3$

$\rightarrow CFCl_3$

Example 2: Chemical formula of R_{22}

$R_{22} = R_{022} = R(m-1)(n+)_P$

$M - 1 = 0 \quad n + 1 = 2 \quad p = 2$

$M = 1 \quad n = 0$

$N + p + q = 2m + 2$

$\Rightarrow 1 + 2 + q = 2 + 2$

$\Rightarrow q = 1$

$C_m\, H_n\, F_p\, Cl_q = C_1\, H_1\, F_2\, Cl$

$= CHClF_2$

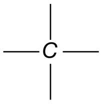
Example 3: $C_2\, H_2\, F_4 \rightarrow R - 134a$

Short cut: To designate saturated hydrocarbons

1st digit $\rightarrow$ I digit + 1 $\rightarrow$ No. of carbon 'C' atoms

2nd digit $\rightarrow$ II digit – 1 $\rightarrow$ No. of hydrogen 'H' atoms

3rd digit $\rightarrow$ III digit $\rightarrow$ No. of fluorine 'F' atoms

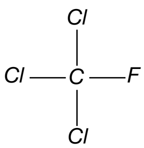
- Carbon valency – 4
- Distribute F and H atoms
- Remaining atoms are Cl 

Example 4: $R_{11} = R_{011}$

$\rightarrow$ No. of 'C' atoms = 0 + 1 = 1

$\rightarrow$ No. of 'H' atoms = 1 – 1 = 0

$\rightarrow$ No. of 'F' atoms = 1



$\therefore CFCl_3$ or CCl_3F

Similarly,

$R_{11} - CCl_3F$

$R_{12} - CCl_2F_2$

$R_{13} - CClF_3$

$R_{22} - CHClF_2$

$R_{134} - C_2H_2F_4$

Case (2): If the refrigerant is unsaturated hydro carbon

Formula: $C_mH_nF_pClq$

Designated as $R(m-1)\ (n+1)P$

where $n + p + q = 2m$

Example 5: R_{115}

$M - 1 = 1 \quad n + 1 = 5 \quad p = 0$

$M = 2 \quad n = 4$

$4 + p + q = 2m$

$4 + q = 4;\ q = 0$

$\therefore \quad C_mH_nF_pCl_q \rightarrow C_2H_4$

Case (3):

Refrigerant is inorganic compound:

Formula: R_{700} + molecular weight

(i) $NH_3 = R_{700+14+3} = R_{717}$

(ii) $CO_2 = R_{700+12+32} = R_{744}$

(iii) $SO_2 = R_{700+32+32} = R_{764}$

(iv) $H_2O = R_{700+2+16} = R_{718}$

(v) Air $= R_{729}$

$N - 7$

$C - 6$

$O - 8$

$S - 16$

Case (4): Azeotropes are the mixture as refrigerants which behave as pure substance and they are designated with R_{500}.

Applications of Refrigerants

Refrigerant	Application
R_{11}	Central air conditioning
R_{12}	Domestic refrigerator, water cooler
R_{22}	Window type air conditioner
R_{113}	Air conditioning
NH_3	Cold storage, ice plants, refrigerators
H_2O	Water, Li-Br absorption system
CO_2	Used as dry ice in transport

Leakage detection of refrigerants:
SO_2: NH_3 swab test
NH_3: Detected by burning sulphur candle
Halocarbon: Halide torch test Hydro carbon
and prop acre: Soap and water test
Refrigeration equipment: Electronic leak detection high sensitivity.

Refrigeration Cycles

Vapour Compression Refrigeration Cycle

Components:

(1) Compressor
(2) Condenser
(3) Expansion valve
(4) Evaporator

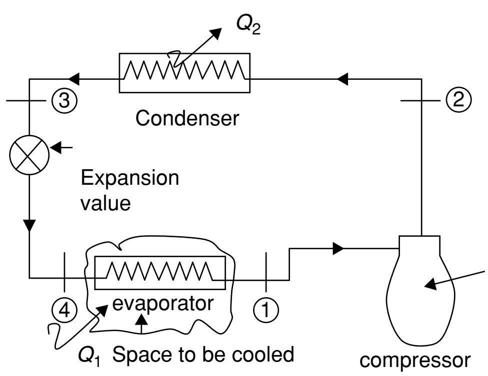
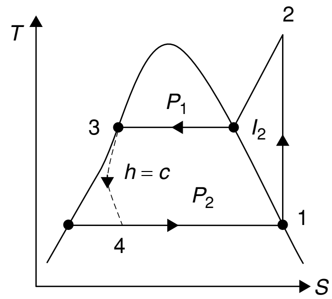
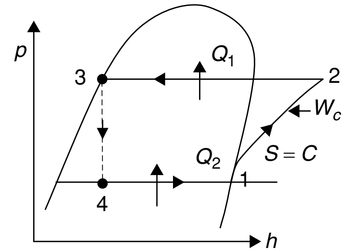


Figure 1 Simple vapour compression refrigeration plant.

1 – 2: Reversible adiabatic compression process
2 – 3: Reversible constant pressure heat rejection process
3 – 4: Adiabatic throttling process
4 – 1: Reversible constant pressure heat absorption



T–S diagram



P–h diagram

Compressor: $h_1 + W_c = h_2$; $W_c = (h_2 - h_1)$ kJ/kg
Condenser: $h_2 = Q_1 + h_3$; $Q_1 = (h_2 - h_3)$ kJ/kg
Expansion valve: $h_3 = h_4$

$$h_{f_3} = h_{f_4} + x_4\, h_{fg4}$$

$$\Rightarrow x_4 = \frac{h_{f_3} - h_{f_4}}{h_{fg_4}}$$

Evaporator: $h_4 + Q_2 = h_1$
$Q_2 = (h_1 - h_4)$ kJ/kg
'Q_2' is called refrigerating effect, i.e., the amount of heat removed form the surroundings per unit mass flow of refrigerant.

$$\therefore \quad \text{COP} = \frac{\text{Refrigeration effect}}{\text{Compression work}} = \frac{Q_2}{W_c} = \frac{h_1 - h_4}{h_2 - h_1}$$

NOTES

1. Rate of heat removal from the surroundings
$$= w(h1 - h4) \text{ kJ/S} = W(h1 - h4) \times 3600 \text{ kJ/h}$$
where W = mass flow in kg/s
2. One tonne of refrigeration:
It is defined as the rate of heat removed from the surroundings equivalent to the heat required for melting 1 tonne of ice in one day.
$$1 \text{ tonne } = \frac{1000 \times 336}{24} = 14{,}000 \text{ kJ/h}$$
• Latent heat of fusion of ice = 336 kJ/kg
3. Capacity of the refrigerating plant
$$\frac{W(h_1 - h_4) \times 3600}{14{,}000} \text{tonnes}$$

4. Volumetric efficiency of compressor:

(a)

$$\eta_{vol} = \frac{\text{Actual volume of gas drawn at evaporator pressure and temperatue}}{\text{piston displacement}}$$

Volume of gas handled by the compressor

$$= W \cdot V_1(\text{m}^3/\text{S}) = \left(\frac{\pi}{4}D^2 L \frac{N}{60} n\right) \times \eta_{Vol}$$

where

W = refrigerant flow rate

$V1$ = specific volume

D = diameter of piston in the compressor

L = stroke of Length

N = number of cylinders

N = rpm

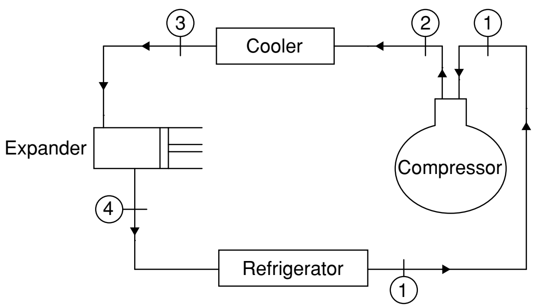
(b) Clearance volumetric efficiency

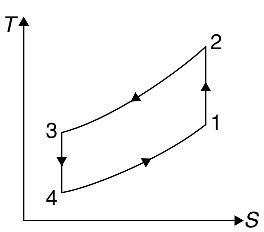
$$\eta_{Vol} = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

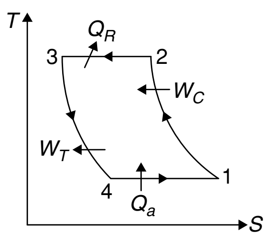
where C = clearance

Bell-Coleman cycle or Reversed Brayton cycle or Reversed Joule cycle

Gas refrigeration cycle works on reverse Brayton cycle or Bell-Coleman cycle or reversed Joule cycle. The schematic diagram is shown below:







1 – 2 → Reversible adiabatic compression

2 – 3 → Constant pressure heat rejection

3 – 4 → Reversible adiabatic expansion

4 – 1 → Constant pressure heat absorption

Here phase of working fluid (gas) is not changing and hence terms like condenser, evaporator are not used, and ideal gas equation can be applied.

Isentropic expansion is used in place of throttling because throttling of gas leads to no temperature change or drop [$h_3 = h_4 \Rightarrow T_3 = T_4$] and hence refrigerant (gas) cannot absorb heat from the storage space. If isentropic expansion is used, there is an appreciable temperature drop and hence refrigerant can absorb heat from the storage space.

→ Net Refrigerant effect, $RE = C_P(T_1 - T_4)$

→ Net work transfer, $W_{net} = C_P[(T_2 - T_1) - (T_3 - T_4)]$

→ Heat addition $(Q_a) = RE = C_P(T_1 - T_4)$

$$\rightarrow \text{COP} = \frac{RE}{W_{net}} = \frac{C_P(T_1 - T_4)}{C_P[(T_2 - T_1) - (T_3 - T_4)]}$$

$$\text{or COP} = \frac{1}{\left[\frac{T_2 - T_3}{T_1 - T_4}\right] - 1}$$

1 – 2 → Reversible adiabatic process

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma 1}{\gamma}} \Rightarrow \frac{T_2}{T_1} = (r_P)^{\frac{\gamma-1}{\gamma}} \quad (1)$$

3 – 4 → Reversible adiabatic expansion

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \frac{T_3}{T_4} = (r_P)^{\frac{\gamma-1}{\gamma}} \quad (2)$$

From equation (1) and (2)

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_2}{T_3} = \frac{T_1}{T_4}$$

$$\Rightarrow \frac{T_2}{T_3} - 1 = \frac{T_1}{T_4} - 1 \Rightarrow \frac{T_2 - T_3}{T_1 - T_4} = \frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \text{COP} = \frac{1}{\frac{T_3}{T_4} - 1} = \frac{T_4}{T_3 - T_4}$$

$$\text{or COP} = \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}} - 1}$$

Solved Examples

Example 1: In a sample of moist air at standard pressure of 100 kPa and 27°C, the particle pressure of water vapour is 1.4 kPa. If the saturation pressure of water vapour is 3.5 kPa at 27°C, then what are the humidity ratio and relative humidity of moist air sample?

(A) 0.00883 and 1.40% (B) 0.00883 and 40%

(C) 0.01561 and 1.40% (D) 0.01561 and 40%

Solution:

Given: $P_t = 100$ kPa, DBT = 27°C

$PV = 1.4$ kPa, $P_{VS} = 3.5$ kPa

Humidity ratio, $\omega = 0.622\left(\frac{P_V}{P_t - P_v}\right)$

$$\Rightarrow \quad \omega = 0.622 \times \frac{1.4}{100 - 1.4} = 0.00883 \frac{\text{kg of } w.v}{\text{kg of } d.a}$$

Relative humidity, $\phi = \frac{P_V}{P_{VS}} = \frac{1.4}{3.5} = 0.4$ or 40%

Example 2: A room contains 40 kg of dry air and 0.5 kg of water vapour. The total pressure and temperature of air in the room are 100 kPa and 27°C, respectively. Given that the saturation pressure for water at 27°C is 3.2 kPa, the relative humidity of the air in the room is

(A) 64.32% (B) 52.34% (C) 61.56% (D) 67.36%

Solution:

$m_a = 40$ kg, $m_v = 0.5$ kg, $P_t = 100$ kPa

DBT = 27°C, $P_{VS} = 3.2$ kPa

$$\omega = \frac{m_v}{m_a} = 0.622\left(\frac{P_V}{P_t - P_v}\right) \Rightarrow \frac{0.5}{40} = 0.622\left(\frac{P_v}{100 - P_v}\right)$$

$\Rightarrow P_v = 1.97$ kPa

$$\therefore \quad \phi = \frac{P_v}{P_{VS}} = \frac{1.97}{3.2} = 0.61564 \text{ or } 61.56\%$$

Example 3: Match the following List-I and List-II.

	List-I		List-II
(P)	Cooling and dehumidification	(1)	DB increases and *DP* Decreases
(Q)	Chemical dehumidification	(2)	*DP* increases and *DB* is Constant
		(3)	*DB* and *WB* both decreases
		(4)	*DB* decreases and *DP* increases

Here, *DB* = Dry bulb temperature

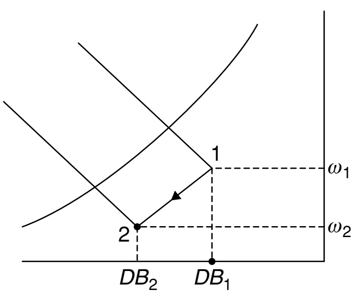
DP = Dew point temperature

WB = Wet bulb temperature

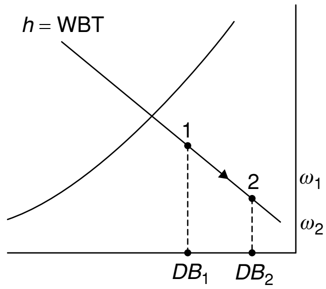
(A) *P*–3, *Q*–1 (B) *P*–1, *Q*–3

(C) *P*–4, *Q*–2 (D) *P*–2, *Q*–4

Solution:



DB decreases and
WB also decreases



DB increases and
DP decreases

Example 4: Air enters a window A/C system at 101.3 kPa, 30°C and 80% RH with mass flow rate of 11 kg of dry air/min with enthalpy of 85 kJ/kg of da. The air is cooled and dehumidified in the system and comes out with specific humidity of 8 gm of wv/kg of the da at enthalpy of 43 kJ/kg of da. If the enthalpy of condensate water is 67 kJ/kg, then the cooling load or load capacity (in kW) of the coil will be (Assume the saturation pressure of water at 30°C = 4.2469 kPa ; da = dry air; *wv* = water vapour)

(A) 6.42 (B) 8.23 (C) 7.12 (D) 7.55

Solution:

$$\phi_1 = 0.8 = \frac{P_v}{P_s} \quad \Rightarrow \quad P_V = 3.3975 \text{ kPa}$$

$$\therefore \quad \omega_1 = 0.622\frac{P_v}{P - P_v} = 0.622 \times \frac{3.3975}{101.3 - 3.3975}$$

$\Rightarrow \omega_1 = 0.0216$ kg of w.v/kg of d.a

$$Q = \frac{11}{60} \times [42] - m_w h_f$$

$$m_w = m_{a1}[\omega_1 - \omega_2] = \frac{11}{60}[0.0216 - 0.008]$$

$\Rightarrow m_w = 0.00249$ kg of w.v/kg of d.a

$$\therefore \quad Q = \frac{11}{60} \times 42 - 0.00249 \times 43$$

$\Rightarrow Q = 7.548$ kW

Example 5: An ice making plant using refrigerant *R*–12 is having an evaporator saturation temperature of –25°C and the condenser saturation temperature of 35°C. The vapour is leaving the compressor at 65°C.

Table 1 *Saturated properties of refrigerant (table)*

Temperature (°C)	Pressure (kPa)	h_f(kJ/kg)	h_g(kJ/kg)
–25°C	123.7	13.3	176.5
35°C	850	69.6	201.5

Superheated table

At *P* = 850 kPa and *T* = 65°C, *h* = 225.5 kJ/kg

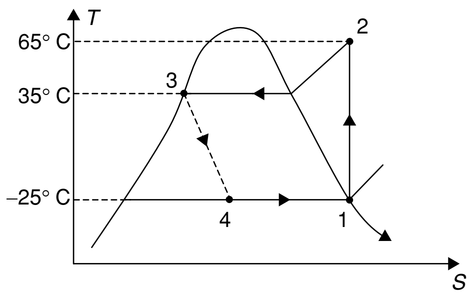
(1) Calculate the COP of the system

(A) 3.78 (B) 2.73 (C) 3.18 (D) 2.18

(2) If the capacity of plant is 5 kW then find the mass flow rate (in kg/s) of refrigerant and power consumption (in kW).

(A) 0.0512 and 3.1 (B) 0.0467 and 2.3
(C) 0.0123 and 2.6 (D) 0.0572 and 2.3

Solution:



Given: $h_4 = h_3 = 69.6$ kJ/kg
$h_5 = 201.5$ kJ/kg, $h_1 = 176.5$ kJ/kg
$h_2 = 225.5$ kJ/kg

$$\text{COP} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{176.5 - 69.6}{225.5 - 176.5}$$

(1) COP = 2.18

Choice (D)

(2) $Q_{add} = 5 \text{ kW} = m(h_1 - h_4)$

$$\Rightarrow \quad m = \frac{5}{176.15 - 69.6} = 0.0467 \text{ kg/sec}$$

$\therefore W_C = m(h_2 - 0_1) = 0.0467(225.5 - 176.5)$

$\Rightarrow W_c = 2.288$ kW

Choice (B)

Exercises

Practice Problems I

1. A mixture of air and water vapour exists at 1 bar pressure and temperature 35°C. Its relative humidity is 75%. Given that the saturation pressure for water vapour at 35°C is 0.05622 bar, the specific humidity in kj/kg of dry air is

(A) 0.029 (B) 0.027
(C) 0.025 (D) 0.020

2. For air with a relative humidity of 80%

(A) dry bulb temperature is less than the wet bulb temperature.
(B) The dew point temperature is less than wet bulb temperature.
(C) The dew point and wet bulb temperatures are equal.
(D) The dry bulb and dew point temperature are equal.

3. Air (atmospheric pressure) at a dry bulb temperature of 42°C and wet bulb temperature of 25°C is humidified in an air washer operating with continuous water recirculation. The wet bulb depression (i.e., the difference between the dry and wet bulb temperatures) at the exit is 27% of that at the inlet. The dry bulb temperature at the exit of the air washer is closest to

(A) 10°C (B) 20°C
(C) 30°C (D) 40°C

4. A moist air sample has dry bulb temperature of 32.9°C and specific humidity of 12 g of water vapour per kg dry air. Assume molecular weight of air as 28.93. If the saturation vapour pressure of water at 32.9°C is 0.050 bar and total pressure is 90 kPa, then the relative humidity (in %) of the sample is

(A) 34.06 (B) 42.0
(C) 25 (D) 30

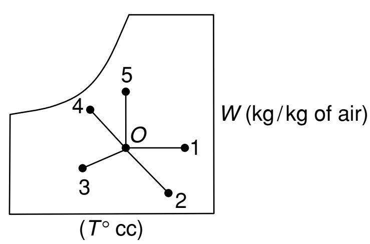
5. A room contains 30 kg of dry air and 0.5 kg of water vapour. The total pressure and temperature of air in the room are 95 kPa and 25°C, respectively. Given that the saturation pressure for water at 25°C is 3.17 kPa, then the relative humidity of the air in the room is

(A) 82% (B) 80%
(C) 79% (D) 78%

6. Various psychometric processes are shown in the figure below:

Process in figure
P. 0 – 1
Q 0 – 2
R. 0 – 3
S. 0 – 4
T. 0 – 5

Name of the process
1. Sensible heating
2. Chemical dehumidification
3. Cooling and dehumidification
4. Humidification with steam injection
5. Humidification with water injection



(A) $P-1, Q-2, R-3, S-4, T-5$
(B) $P-1, Q-5, R-4, S-2, T-3$
(C) $P-1, Q-2, R-3, S-5, T-4$
(D) $P-4, Q-3, R-2, S-1, T-5$

7. The least power required for a perfect reversed heat engine that makes 500 kg of ice per hour at –5°C from

feed water at 20°C is, take specific heat of ice as 2.095 and latent heat 335 kJ/kg.
(A) 2 kW (B) 3.5 kW
(C) 4.7 kW (D) 5.55 kW

8. The COP of a refrigerating plant is 30% of the COP of the Carnot cycle while working between the temperature limit of –4° and 25°C. The compressor of the refrigerating plant is driven by a motor of 70 kW under the assumption of 100% mechanical efficiency. The capacity of the plant in tonnes is
(A) 60.5 (B) 55.3
(C) 58.5 (D) 60.5

9. The atmospheric air at *DBT* 17°C enters a heating coil maintained at 40°C. If the air leaves the heating coil at 28°C, the coil efficiency would be equal to
(A) 47.8% (B) 50%
(C) 52% (D) 550.2%

Direction for questions 10 and 11: A vapour compression refrigerator system works between the pressure limits 50 bar and 10 bar. The working fluid is just dry at the end of compression and there is no under cooling of the fluid before expansion valve. Fluid flow rate is at the rate of 3 kg/min.

P (bar)	**t_s(°c)**	**h_f kJ/kg**	**h_g kJ/kg**	**S_f (kJ/Kgk)**	**S_g kJ/Kgk**
50	285	141.56	275.45	0.452	1.0225
10	223	45.32	300.56	02.16	1.1564

10. The dryness fraction of the vapour refrigerant entering the compressor is
(A) 0.7546
(B) 0.8576
(C) 0.8765
(D) 0.92

11. The refrigeration effect in kJ/kg is
(A) 55.14 (B) 85.25
(C) 100 (D) 122.65

Direction for questions 12 and 13:
An ammonia refrigeration system operates between temperature limits of –14°C and 28°C. The machine circulates 5 kg/min. There is no under cooling. The temperature after isentropic compression is 75°C.

Temperature (°C)	**Pressure (kP_a)**	**Enthalpy (kJ/kg)**		**Entropy (kJ/kgk)**	
		h_f	**h_g**	**s_f**	**s_g**
–14	246.5	109.5	1420.5	0.435	5.543
28	1098.71	318.2	1455	1.2028	4.995

12. COP of refrigeration system is
(A) 2.5 (B) 3.43
(C) 5.26 (D) 10.2

13. The Displacement volume for the compressor in m^3/min. Neglect clearance.
(A) 2.5 (B) 3.5
(C) 4 (D) 6.5

Direction for questions14 and 15: An ammonia refrigerator produces 15 tonnes of ice from and 0°C in a day of 24 hours. The temperature range of the working cycle is 25°C and –15°C. The ammonia vapour is dry and saturated at the end of compression.
Assume actual COP is 60% of theoretical.

14. The power required to drive the compressor in kW is
(A) 25.06 (B) 20.06
(C) 15.52 (D) 10.45

15. Mass flow rate in kg/min is
(A) 4.45 (B) 5.65
(C) 0.25 (D) 0.45

Use ammonia table as given below:

Temperature (°C)	**Specific enthalpy (kJ/kg)**		**Specific entropy (kJ/kgk)**	
	f_f	**h_g**	**s_f**	**s_g**
25	380.74	1319.21	0.3473	4.4897
–15	–54.56	130.99	–0.2134	5.0585

Practice Problems 2

1. Dew point temperature is the temperature at which condensation begins when the air is cooled at constant _____.
(A) volume (B) entropy
(C) pressure (D) enthalpy

Direction for questions 2 and 3: The atmospheric conditions are 25°C DBT and specific humidity of 15 gm/kg of air. Saturated vapour pressure at 25°C is 0.03243 bar.

2. The partial pressure of vapour in bar is
(A) 0.0235 (B) 0.0205
(C) 0.015 (D) 0.010

3. Relative humidity in % is
(A) 72.9 (B) 70
(C) 65.4 (D) 63.5

4. 100 cubic m of air per minute at 15°C DBT and 85% RH is heated until its temperature becomes 22°C then heat added to the air per min is (Saturated vapour pressure at 22°C is 0.0124 bar)
(A) 900.2 kJ/min (B) 877.08 kJ/min
(C) 650 kJ/min (D) 552.5 kJ/min

5. For the above problem, at 22°C saturation pressure is 0.02694, than the relative humidity in % is
(A) 65.5 (B) 60.4
(C) 55.3 (D) 50.3

Direction for questions 6 and 7: An air refrigerator works between pressure limits of 1 bar and 5 bar. The temperature of the air entering the compressor is 17°C and entering the expansion cylinder is 27°C.

The expansion follows the law $PV^{1.25}$ = constant The compression follows the law $PV^{1.35}$ = constant

Take for air, Cp = 1 kJ/kg-K and Cv = 0.7 kJ/kg- K then

6. COP of the refrigerating cycle is
(A) 1.2 (B) 2.5
(C) 3.8 (D) 4.3

7. If air circulation through the system is 20 kg/min, find the refrigeration capacity of the system.
(A) 7.2 tons (B) 6.9 tons
(C) 5.4 tons (D) 1 tons

Direction for questions 8 to 10: An air refrigerator working on Bell–Coleman cycle takes air into the compressor 1 bar and –6°C. It is compressed in the compressor to 6 bar and cooled to 25°C at the same pressure. It is further expanded in the chamber to 1 bar discharged to take the cooling load.
The isentropic efficiency of the compressor = 85%
The isentropic efficiency of the expander = 90%
Then find

8. The refrigeration capacity of the system if the air circulation is 35 kg/min
(A) 10 tons (B) 11 tons
(C) 12.75 tons (D) 50.25 tons

9. KW capacity of the motor required to run the compressor
(A) 100 (B) 60
(C) 50 (D) 20

10. COP of the cycle.
(A) 1.25 (B) 2.56
(C) 0.74 (D) 0.55

11. An air refrigerator works between the pressure limit of 1 bar and 7 bar. The temperature of the air entering the compressor and expansion cylinder are 12°C and 25°C, respectively. Find the length and diameter of a single acting compressor in cm, if the compressor runs at 300 rpm. and the volumetric efficiency is 85%, take m = 50 kg/min.
(A) 52, 78 (B) 78, 55
(C) 105, 78 (D) 205, 105

12. The enthalpies at the beginning of compression, at the end of compression and at the end of condensation are respectively 187 kJ/kg, 208 kJ/kg and 87 kJ/kg. The COP of the vapour compression refrigeration system is
(A) 3.5 (B) 3.78
(C) 4.2 (D) 4.76

13. For an air conditioning system, the outdoor and indoor design dry bulb temperatures are 50°C and 25°C, respectively. The space to be air conditioned is 25 m × 35 m × 10 m. The density and specific heat of air are 1.2 kg of dry air/m^3 hour and 1.02 kJ/kg of dry air, respectively. Then the sensible heat load due to infiltration is
(A) 74.37 kW (B) 50 kW
(C) 25.5 kW (D) 12.53 kW

14. In an ideal vapour compression refrigeration cycle, the specific enthalpy of refrigerant at the following state is given as (kJ/kg)

Inlet of the condenser	:	285
Exit of condenser	:	115
Exit of evaporator	:	235

The COP of this cycle is
(A) 4.5 (B) 3.4
(C) 2.8 (D) 2.4

15. The working temperatures in evaporator and condenser coils of a refrigerator are –25°C and 30°C, respectively. The COP of the refrigerator is 0.85 of the maximum COP for a power input of 2 kW. The refrigeration effect produced will be
(A) 7.6 kW (B) 9 kW
(C) 10.2 kW (D) 12 kW

16. Horse power and kW required per tonne of refrigeration is expressed as
(A) $\frac{4.5}{\text{COP}}$ and $\frac{3.75}{\text{COP}}$
(B) $\frac{4.75}{\text{COP}}$ and $\frac{3.50}{\text{COP}}$
(C) $\frac{4.75}{\text{COP}}$ and $\frac{3.75}{\text{COP}}$
(D) 4.75 × COP and 3.5 COP

17. The COP of domestic refrigerator is
(A) equal to 1 (B) less than 1
(C) more than 1 (D) None of the above

18. Thermoelectric refrigeration system is based on
(A) Peltier effect (B) Seebeck effect
(C) Joule effect (D) None of these

19. Air refrigeration cycle is used in
(A) Commercial refrigerators
(B) Domestic refrigerators
(C) Gas liquefaction
(D) Air conditioning

20. Which one of the following is the correct alternative?
(A) $\mu = \phi\left[\dfrac{1-\frac{P_v}{P}}{1-\frac{P_s}{P}}\right]$ (B) $\mu = \phi\left[\dfrac{1-\frac{P_s}{P}}{1-\frac{P_v}{P}}\right]$
(C) $\phi = \mu\left[\dfrac{1-\frac{P_s}{P}}{1-\frac{P_v}{P}}\right]$ (D) $\phi = \dfrac{1}{\mu}\left[\dfrac{1-\frac{P_v}{P}}{1-\frac{P_s}{P}}\right]$

21. In on-off control refrigeration system, which one of the following expansion devices is used?

(A) Thermostat
(B) Capillary tube
(C) Automatic expansion valve
(D) Float valve

22. Which one of the following refrigerants has the highest critical temperature?
(A) Co_2 (B) So_2
(C) H_2o (D) NH_3

23. If during the sensible cooling B is the bypass factor, then coil efficiency is given by
(A) $1 - B$ (B) $B - 1$
(C) $\frac{1}{B}$ (D) $\frac{1}{1-B}$

24. On Psychrometric chart, relative humidity lines are
(A) vertical (B) horizontal
(C) inclined (D) curved

25. In the window air conditioner, the expansion device used is
(A) capillary tube
(B) thermostatic expansion valve
(C) automatic expansion valve
(D) float valve

26. If a mass of moist air in an airtight vessel is heated to a higher temperature, then
(A) relative humidity of the air increases
(B) relative humidity of the air decreases
(C) specific humidity of the air increases
(D) specific humidity of the air decreases

27. At 100% relative humidity, the wet bulb temperature is
(A) equal to ambient temperature
(B) same as dew point temperature
(C) less than dew point temperature
(D) more than dew point temperature

28. The comfort conditions in air conditioning system are defined by
(A) 22°C DBT and 60% RH
(B) 25°C DBT and 100% RH
(C) 20°C DBT and 75% RH
(D) 27°C DBT and 75% RH

29. Which of the following element responsible for ozone depletion?
(A) Chlorine (B) Fluorine
(C) Carbon (D) Hydrogen

30. The wet bulb depression is zero, when relative humidity is equal to
(A) 100% (B) 60%
(C) 40% (D) zero

31. Theoretical maximum COP of a vapour absorption system (where, T_G = generator temperature, T_E = evaporator temperature, T_O = environmental temperature) is
(A) $\frac{T_G}{T_E}\left(\frac{T_O - T_E}{T_G - T_O}\right)$ (B) $\frac{T_G}{T_E}\left(\frac{T_G - T_O}{T_O - T_E}\right)$
(C) $\frac{T_E}{T_G}\left(\frac{T_O - T_E}{T_G - T_O}\right)$ (D) $\frac{T_E}{T_G}\left(\frac{T_G - T_O}{T_O - T_E}\right)$

32. If P_a and P_v denote the partial pressure of dry air and that of water vapour in moist air, the specific humidity of air is given by
(A) $\frac{0.622P_v}{P_a + P_v}$ (B) $\frac{0.622P_v}{P_a}$
(C) $\frac{P_v}{P_a + P_v}$ (D) $\frac{P_v}{P_a}$

33. When air is adiabatically saturated, the temperature attained is
(A) dew point temperature
(B) dry bulb temperature
(C) wet bulb temperature
(D) triple point temperature

34. In a vapour compression system, the working fluid is super heated vapour at entrance to
(A) evaporator (B) condenser
(C) compressor (D) expansion valve

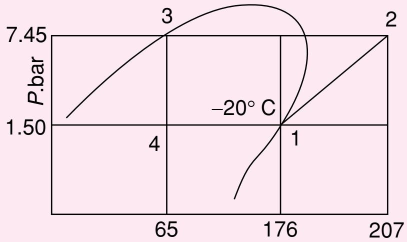
Previous Years' Questions

1. During chemical dehumidification process of air **[2004]**
(A) dry bulb temperature and specific humidity decrease
(B) dry bulb temperature increases and specific humidity decreases
(C) dry bulb temperature decreases and specific humidity increases
(D) dry bulb temperature and specific humidity increase

2. Environment friendly refrigerant R134 is used in the new generation domestic refrigerators. Its chemical formula is **[2004]**
(A) $CHCIF_2$ (B) $C_2CI_3F_3$
(C) $C_2CI_2F_4$ (D) $C_2H_2F_4$

3. Dew point temperature of air at one atmospheric pressure (1.013 bar) is 18°C. The air dry bulb temperature is 30°C. The saturation pressure of water at 18°C and 30°C are 0.02062 bar and 0.04241 bar, respectively. The specific heat of air and water vapour respectively. The specific latent heat of vaporization of water at 0°C is 2500 kJ/kg. The specific humidity (kg/kg of dry air) and enthalpy (kJ/kg of dry air) of this moist air respectively, are **[2004]**
(A) 0.01051, 52.64 (B) 0.01291, 63.15
(C) 0.01481, 78.60 (D) 0.01532, 81.40

4. A R-12 refrigerant reciprocating compressor operates between the condensing temperature of 30°C and evaporator temperature of –20°C. The clearance volume ratio of the compressor is 0.03. Specific heat ratio of the vapour is 1.15 and the specific volume at the suction is 0.1089 m^3/kg. Other properties at various states are given in the figure. To realize 2 tons of refrigeration, the actual volume displacement rate considering the effect of clearance is **[2004]**

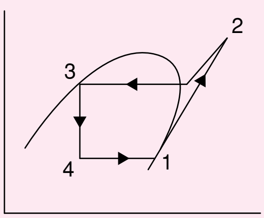


(A) 6.35×10^{-3} m^3/s
(B) 63.5×10^{-3} m^3/s
(C) 635×10^{-3} m^3/s
(D) 4.88×10^{-3} m^3/s

5. For a typical sample of ambient air (at 35°C, 75% relative humidity and standard atmospheric pressure), the amount of moisture in kg per kg of dry air will be approximately **[2005]**
(A) 0.002
(B) 0.027
(C) 0.25
(D) 0.75

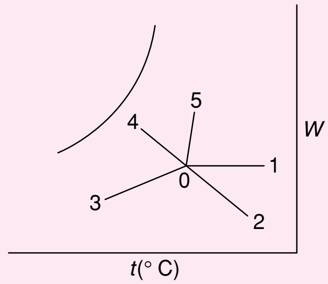
6. Water at 42° is sprayed into a stream of air at atmospheric pressure, dry bulb temperature of 40°C and a wet bulb temperature of 20°C. The air leaving the spray humidifier is not saturated. Which of the following statements is true? **[2005]**
(A) Air gets cooled and humidified
(B) Air gets heated and humidified
(C) Air gets heated and dehumidified
(D) Air gets cooled and dehumidified

7. The vapour compression refrigeration cycle is represented as shown in the figure below, with state 1 being exit of the evaporator. The coordinate system used in this figure is **[2005]**



(A) *p-h*
(B) *T-s*
(C) *p-s*
(D) *T-h*

8. Various psychrometric processes are shown in the figure below:



Process in Figure	Name of the process
P. 0 – 1	I. Chemical dehumidification
Q. 0 – 2	II. Sensible heating
R. 0 – 3	III. Cooling and dehumidification
S. 0 – 4	IV. Humidification with steam injection
T. 0 – 5	V. Humidification with water Injection

[2005]

(A) *P* – I, *Q* – II, *R* – III, *S* – IV, *T* – V
(B) *P* – II, *Q* – I, *R* – III, *S* – V, *T* – IV
(C) *P* – II, *Q* – I, *R* – III, *S* – IV, *T* – V
(D) *P* – III, *Q* – IV, *R* – V, *S* – I, *T* – II

9. Dew point temperature is the temperature at which condensation begins when the air is cooled at constant. **[2006]**
(A) volume
(B) entropy
(C) pressure
(D) enthalpy

10. The statements concern psychrometric chart.
1. Constant relative humidity lines are uphill straight lines to the right
2. Constant wet bulb temperature lines are downhill straight lines to the right.
3. Constant specific volume lines are down hill straight lines to the right.
4. Constant enthalpy lines are coincident with constant wet bulb temperature lines.

Which of the statements are correct? **[2006]**
(A) 2 and 3
(B) 1 and 2
(C) 1 and 3
(D) 2 and 4

11. A thin layer of water in field is formed after a farmer has watered it. The ambient air conditions are: temperature 20°C and relative humidity 5%, An extract of steam tables is given below.

Temperature (°C)	–15	–10	–5	0.01	5	10	15	20
Saturation pressure (kPa)	0.10	0.26	0.40	0.61	0.87	1.23	1.71	2.34

Neglecting the heat transfer between the water and the ground, the water temperature in the field after phase equilibrium is reached equals **[2006]**

(A) 10.3°C (B) −10.3°C
(C) −14.5°C (D) 14.5°C

12. Atmospheric air at a flow rate of 3 kg/s (on dry basis) enters a cooling and dehumidifying coil with an enthalpy of 85 kJ/kg of dry air and humidity ratio of 19 grams/kg of dry air. The air leaves the coil with an enthalpy of 43 kJ/kg of dry air and a humidity ratio of 8 grams/kg of dry air. If the condensate water leaves the coil with an enthalpy of 67 kJ/kg, the required cooling capacity of the coil in kW is **[2007]**

(A) 75.0 (B) 123.8
(C) 128.2 (D) 159.0

13. Moist air at a pressure of 100 kPa is compressed to 500 kPa and then cooled to 35°C in an after cooler. The air at the entry to the after cooler is unsaturated and becomes just saturated at the exit of the after cooler. The saturation pressure of water at 35°C is 5.628 kPa. The partial pressure of water vapour (in kPa) in the moist air entering the compressor is closest to **[2008]**

(A) 0.57 (B) 1.13
(C) 2.26 (D) 4.52

14. Air (at atmospheric pressure) at a dry bulb temperature of 40°C and wet bulb temperature of 20°C is humidified in an air washer operating with continuous water recirculation. The wet bulb depression (i.e., the difference between the dry and wet bulb temperatures) at the exit is 25% of that at the inlet. The dry bulb temperature at the exit of the air washer is closest to **[2008]**

(A) 10°C (B) 20°C
(C) 25°C (D) 30°C

15. In an ideal vapour compression refrigeration cycle, the specific enthalpy of refrigerant (in kJ/kg) at the following states is given as:

Inlet of condenser: 283
Exit of condenser: 116
Exit of evaporator: 232

The COP of this cycle is **[2009]**

(A) 2.27 (B) 2.75
(C) 3.27 (D) 3.75

16. If a mass of moist air in an airtight vessel is heated to a higher temperature, then **[2011]**

(A) specific humidity of the air increases
(B) specific humidity of the air decreases
(C) relative humidity of the air increases
(D) relative humidity of the air decreases

17. A room contains 35 kg of dry air and 0.5 kg of water vapour. The total pressure and temperature of air in the room are 100 kPa and 25°C, respectively. Given that the saturation pressure for water at 25°C is 3.17 kPa, the relative humidity of the air in the room is **[2012]**

(A) 67% (B) 55%
(C) 83% (D) 71%

Direction for questions 18 and 19: A refrigerator operates between 120 kPa and 800 kPa in an ideal vapour compression cycle with R-134a as the refrigerant. The refrigerant enters the compressor as saturated vapour and leaves the condenser as saturated liquid. The mass flow rate of the refrigerant is 0.2 kg/s. Properties for R-134a are as follows:

Saturated *R*–134a

P(kPa)	*T*(°C)	h_f(kJ/kg)	h_g(kJ/kg)	S_f(kJ/kg.K)	S_g(kJ/kg.K)
120	–22.32	22.5	237	0.093	0.95
800	31.31	95.5	267.3	0.354	0.918

Superheated *R*–134a

P(kPa)	*T*(°C)	*h*(kJ/kg)	*S*(kJ/kg.K)
800	40	276.45	0.95

18. The rate at which heat is extracted, in kJ/s from the refrigerated space is **[2012]**

(A) 28.3 (B) 42.9
(C) 34.4 (D) 14.6

19. The power required for the compressor in kW is **[2012]**

(A) 5.94 (B) 1.83
(C) 7.9 (D) 39.5

20. The pressure, dry bulb temperature and relative humidity of air in a room are 1 bar, 30°C and 70%, respectively. If the saturated steam pressure at 30°C is 4.25 kPa, the specific humidity of the room air in kg water vapour/kg dry air is **[2013]**

(A) 0.0083 (B) 0.0101
(C) 0.0191 (D) 0.0232

21. Which one of the following is a CFC refrigerant? **[2014]**

(A) R744 (B) R290
(C) R502 (D) R718

22. A heat pump with refrigerant R22 is used for space heating temperature limits of –20°C and 25°C. The heat required is 200 MJ/h. Assume specific heat of vapour at the time of discharge as 0.98 kJ/kg.K. Other relevant properties are given below. The enthalpy (in kJ/kg) of the refrigerant at isentropic compressor discharge is ____. **2014]**

Saturation temperature	Pressure	Specific enthalpy		Specific entropy	
T_{sat} (°C)	P(MN/m²)	h_f(kJ/kg)	h_g(kJ/kg)	s_f(kJ/kg.K)	s_g(kJ/kg.K)
–20	0.2448	177.21	397.53	0.9139	1.7841
25	1.048	230.07	413.02	1.1047	1.7183

23. A sample of moist air at a total pressure of 85 kPa has a dry bulb temperature of 30°C (saturation vapour pressure of water = 4.24 kPa). If the air sample has a relatively humidity of 65%, the absolute humidity (in gram) of water vapour per kg of dry air is_________. **[2014]**

24. Moist air at 35°C and 100% relative humidity is entering a psychrometric device and leaving at 25°C and 100% relative humidity. The name of the device is **[2014]**

(A) Humidifier (B) Dehumidifier
(C) Sensible heater (D) Sensible cooler

25. A stream of moist air (mass flow rate = 10.1 kg/s) with humidity ratio of 0.01 $\frac{\text{kg}}{\text{kg dry air}}$ mixes with a second stream of superheated water vapor flowing at 0.1 kg/s. Assuming proper and uniform mixing with no condensation, the humidity ratio of the final stream $\left(\text{in } \frac{\text{kg}}{\text{kg dry air}}\right)$ is _______. **[2015]**

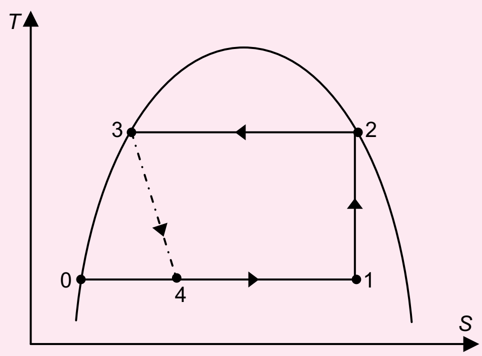
26. Refrigerant vapor enters into the compressor of a standard vapor compression cycle at –10°C (h = 402 kJ/kg) and leaves the compressor at 50°C (h = 432 kJ/kg). It leaves the condenser at 30°C (h = 237 kJ/kg). The COP of the cycle is ____ **[2015]**

27. Air in a room is at 35°C and 60% relative humidity (RH). The pressure in the room is 0.1 MPa. The saturation pressure of water at 35°C is 5.63 kPa. The humidity ratio of the air (in gram/kg of dry air) is ______. **[2015]**

28. The partial pressure of water vapour in a moist air sample of relative humidity 70% is 1.6 kPa, the total pressure being 101.325 kPa. Moist air may be treated as an ideal gas mixture of water vapour and dry air. The relation between saturation temperature (T_s in K) and saturation pressure (p_s in kPa) for water is given by $\ln(p_s/p_o) = 14.317 - 5304/T_s$, where p_o = 101.325 kPa. The dry bulb temperature of the moist air sample (in °C) is _____. **[2016]**

29. In a mixture of dry air and water vapor at a total pressure of 750 mm of Hg, the partial pressure of water vapor is 20 mm of Hg. The humidity ratio of the air in grams of water vapor per kg of dry air (g_w/kg_{da}) is ________. **[2016]**

30. In the vapor compression cycle shown in the figure, the evaporating and condensing temperatures are 260 K and 310 K, respectively. The compressor takes in liquid-vapor mixture (state 1) and isentropically compresses it to a dry saturated vapor condition (state 2). The specific heat of the liquid refrigerant is 4.8 kJ/kg-K and may be treated as constant. The enthalpy of evaporation for the refrigerant at 310 K is 1054 kJ/kg.



The difference between the enthalpies at state points 1 and 0 (in kJ/kg) is ________. **[2016]**

Answer Keys

Exercises

Practice Problems 1

1. B	**2.** B	**3.** C	**4.** A	**5.** D	**6.** C	**7.** D	**8.** B	**9.** A	**10.** B
11. D	**12.** C	**13.** A	**14.** B	**15.** A					

Practice Problems 2

1. B	**2.** A	**3.** A	**4.** B	**5.** D	**6.** C	**7.** B	**8.** C	**9.** B	**10.** C
11. A	**12.** D	**13.** A	**14.** D	**15.** A	**16.** B	**17.** C	**18.** A	**19.** C	**20.** C
21. A	**22.** C	**23.** A	**24.** D	**25.** A	**26.** B	**27.** B	**28.** A	**29.** D	**30.** A
31. D	**32.** B	**33.** C	**34.** B						

Previous Years' Questions

1. B	**2.** D	**3.** B	**4.** A	**5.** B	**6.** B	**7.** D	**8.** B	**9.** C	**10.** A
11. C	**12.** C	**13.** B	**14.** C	**15.** A	**16.** D	**17.** D	**18.** A	**19.** C	**20.** C
21. C	**22.** 430 to 440		**23.** 19 to 22		**24.** B	**25.** 0.02	**26.** 5.5	**27.** 21.7 to 21.9	
28. 19.9	**29.** 16.9–17.1		**30.** Data insufficient						

Test

Theromodynamics

Time: 60 Minutes

Direction for questions 1 to 30: Select the correct alternative from the given choices.

1. An isolated system is one, which
(A) Permits the passage of energy and matter across the boundaries
(B) Permits the passage of energy only
(C) Does not permit the passage of energy and matter across it.
(D) Permits the passage of matter only

2. Control volume refers to a
(A) Specified mass
(B) Fixed region in the space
(C) Closed system
(D) None of these

3. Which of the following is not an extensive property of a thermodynamic system?
(A) Total mass
(B) Total internal energy
(C) Total volume
(D) Temperature

4. Kelvin–Plank's law deals with
(A) Conversion of work into heat.
(B) Conversion of heat into work.
(C) Conservation of work.
(D) Conservation of heat.

5. According to kinetic theory of gases, at absolute to zero
(A) Specific heat of molecules reduces to zero
(B) Kinetic energy of molecules reduces to zero
(C) Volume of gas reduce to zero
(D) Pressure of gas reduce to zero

6. Equal volume of all gasses, at the same temperature and pressure contain equal number of molecules. This is according to
(A) Charle's law. (B) Avagadro's law.
(C) Joule's law. (D) Gay lusssac's law.

7. In an isothermal process, internal energy
(A) Increases. (B) Remains constant.
(C) Decreases. (D) None of these

8. In a throttling process
(A) $W = 0$ (B) $E = 0$
(C) $H = 0$ (D) All of the above

9. The condition for reversibility of a cycle is

(A) $\oint \frac{dQ}{T} < 0$ (B) $\oint \frac{dQ}{T} > 0$

(C) $\oint \frac{dQ}{T} = 0$ (D) None of these

10. Isentropic flow is
(A) Reversible adiabatic flow.
(B) Irreversible adiabatic flow.
(C) Frictionless fluid flow.
(D) None of these

11. The following are examples of some intensive and extensive properties:

(1) Pressure.	(2) Temperature.
(3) Volume.	(4) Velocity.
(5) Electric charge.	(6) Magnetisation.
(7) Viscosity.	(8) Potentail energy.

Which one of the following sets gives the correct combinations of intensive and extensive properties?

	Intensive	Extensive
(A)	1, 2, 3, 4,	5, 6, 7, 8,
(B)	1, 3, 5, 7,	2, 4, 6, 8 ,
(C)	1, 2, 4, 7,	3, 5, 6, 8,
(D)	2, 3, 6, 8,	1, 4, 5, 7

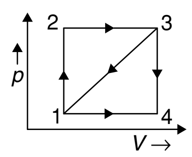
12. Match List-I with List-II

List-I	List-II
a. Heat to work	1. Nozzle
b. Heat to lift weight reaction	2. Endothermic chemical
c. Heat to strain energy	3. Heat engine
d. Heat to electro magnetic	4. Hot air balloon
	5. Thermal radiation
	6. Biometric strips

Codes:

	a	b	c	d		a	b	c	d
(A)	3	4	6	5	(B)	2	3	5	4
(C)	4	5	6	1	(D)	1	2	3	6

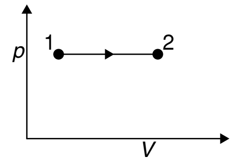
13. Given that the path 1 – 2 – 3 system absorbs 100 kJ heat and does 60 kJ work while along the path 1 – 4 – 3 and does 20 kJ work (see figure given) The heat absorbed during the cycle 1 – 4 – 3 is



(A) –140 kJ (B) –80 kJ
(C) –40 kJ (D) +60 kJ

14. A mixture of gases expands from 0.03 m^3 at a constant pressure of 1MPa and absorbs 84 kJ of heat during the process. The change in internal energy of the mixture is
(A) 30 kJ. (B) 54 kJ.
(C) 84 kJ. (D) 114 kJ.

15. What will be the specific heat of the gas which undergoes the process shown in the $P-V$ diagram?



$P_1 = 5$ kPa
$W_{1-2} = 25$ kJ
$V_2 = 10$ m^3
$U_2 - U_1 = 20$ kJ and $t_2 = 327$°C

(A) 50 kJ/k (B) 50 kJ/k
(C) 150 kJ/k (D) 150 kJ/k

16. Specific heat of a gas, $C_P = C_V$ at

(A) Absolute zero (B) Critical temperature
(C) Triple point (D) All temperatures

17. A refrigerating machine working on Reversed Carnot cycle takes out 2 kW per minute of heat from the system while working between temperature limits of 300°K and 200°K. The COP and power consumed by the cycle will be

(A) 1, 1 kW. (B) 1, 2 kW.
(C) 2, 1 kW. (D) 2, 2 kW.

Direction for questions 18 and 19: A fluid undergoes a reversible adiabatic compression from 0.5 Mpa, 0.2 m^3 to 0.05 m^3 according to the law $PV^{1.3}$ = Constant

18. Change in enthalpy will be

(A) 123.3 kJ. (B) 153.3 kJ.
(C) 183.3 kJ. (D) 223.3 kJ.

19. Change in internal energy will be

(A) 161.8 kJ. (B) 171.8 kJ.
(C) 181.8 kJ. (D) 191.8 kJ.

Direction for questions 20 and 21: During a constant pressure process in a closed system with $P = 105$ kpa and properties of the system change from $V_1 = 0.025$ m^3, $T_1 = 10$°C, to $V_2 = 0.45$ m^3 and $T_2 = 240$°C. The specific heat at constant pressure of the system is given by

$$C_P = \left(0.4 + \frac{18}{T+40}\right) \text{kj/kg. °K}$$

Assume the mass of the system is 1 kg.

20. The heat transfer will be

(A) 95.43 kJ/kg. (B) 101.68 kJ/kg.
(C) 105.4 kJ/kg. (D) 110.6 kJ/kg.

21. The work transfer will be

(a) 19 kJ/kg. (B) 20 kJ/kg.
(C) 21 kJ/kg. (D) 31 kJ/kg.

Direction for questions 22 and 23: A heat engine is supplied heat at the rate of 1700 kJ/min and gives an output of 9 kW

22. The thermal efficiency will be

(A) 3046%. (B) 31.76%.
(C) 41.66%. (D) 42.43%.

23. The rate of heat rejection will be

(A) 7.33 kJ/sec. (B) 8.33 kJ/sec.
(C) 9.33 kJ/sec. (D) 10.33 kJ/sec.

Direction for questions 24 and 25: At a place where the surroundings are at 1 bar, 27°C a closed rigid thermally insulated tank contains 2 kg of air at 2 bar, 27°C. The air is then churned for a while by a paddle wheel connected to an external motor. It is given that the irreversibility of the process is 100 kJ. Assume for air $C_V = 0.718$ kJ/kg.°K

24. The final temperature will be

(A) 90°C. (B) 95°C.
(C) 100°C. (D) 105°C.

25. The increase in availability will be

(A) 11.5 kJ. (B) 12 kJ.
(C) 12.54 kJ. (D) 13 kJ.

26. For reversible adiabatic compression in a steady flow process the work transfer per unit mass is

(A) $\int pdv$ (B) $\int vdp$.
(C) $\int Tds$. (D) $\int sdT$.

Direction for questions 27 and 28: Air flows steadily at the rate of 0.5 kg/sec through an air compressor entering at 7m/sec velocity, 100kPa pressure and 0.95 m^3/kg volume and leaving at 5m/sec, 700 kPa and 0.19 m^3/kg. The internal energy of leaving air is 90 kJ/kg greater than that of the entering air. Cooling water in the compressor jacket absorbs heat from the air at the rate of 58 kW.

27. The ratio of the inlet pipe diameter to outlet pipe diameter is

(A) 3.21. (B) 2.22.
(C) 2.09. (D) 1.89.

28. The rate of shaft work input is

(A) 68 kW. (B) 108 kW.
(C) 122 kW. (D) 135 kW.

Direction for questions 29 and 30: Air is compressed in a reversible isothermal steady flow process from 1 bar and 40°C to 10 bar. Assume $R = 0.287$ kJ/k.

29. Work done on the gas per kg will be

(A) –206.8 kJ. (B) –210.6 kJ.
(C) –215.6 kJ. (D) –220.6 kJ.

30. The change in entropy will be

(A) –0.5405 kJ/kg. (B) –0.5806 kJ/kg.
(C) –0.6608 kJ/kg. (D) –0.6804 kJ/kg.

Answer Keys

1. C	**2.** B	**3.** D	**4.** B	**5.** B	**6.** B	**7.** B	**8.** D	**9.** C	**10.** A
11. C	**12.** A	**13.** D	**14.** B	**15.** C	**16.** A	**17.** C	**18.** D	**19.** B	**20.** B
21. C	**22.** B	**23.** C	**24.** D	**25.** C	**26.** B	**27.** D	**28.** C	**29.** A	**30.** C