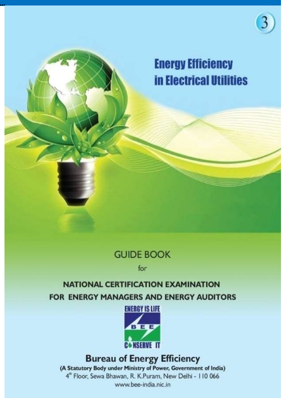
BOOK 3 – ENERGY EFFICIENCY IN ELECTRICAL UTILITIES

Brief Contents

OPTC TRAINING COURSE



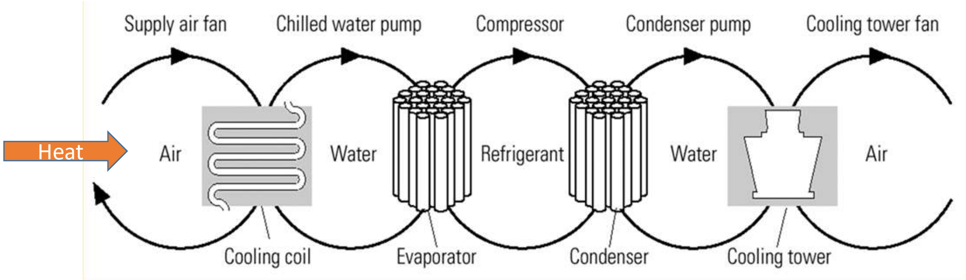
Chapter-4 HVAC and Refrigeration System

Contents

4.1 Introduction

What is a refrigeration? Refrigeration deals with the transfer of heat from a low temperature level at the heat source to a high temperature level at the heat sink by using a low boiling refrigerant. HVAC and refrigeration system transfers the heat energy from or to the products, or building environment.

Conceptual view of a chilled-water air-conditioning system



Thermal energy moves from left to right as it is extracted from the space and expelled into the outdoors through five loops of heat transfer:

4.2 Psychrometrics and Air-Conditioning Processes

What is a Ton of refrigeration?

The cooling effect produced is quantified as tons of refrigeration.

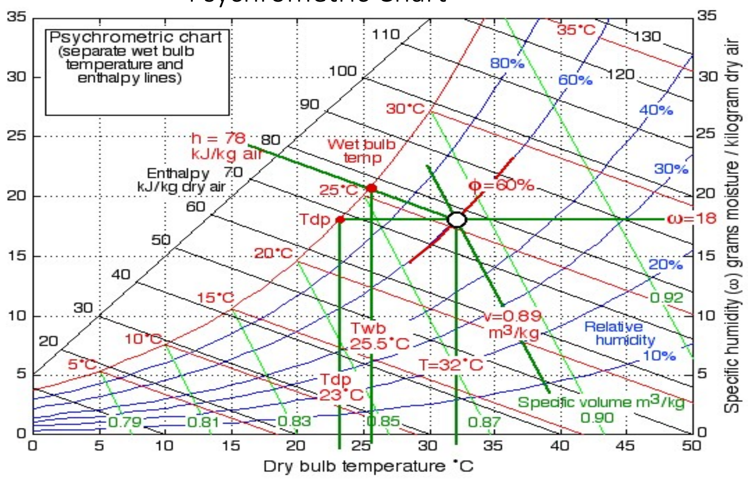
1 ton of refrigeration = 3024 kCal/hr heat rejected.

What is a Psychrometrics?

- **Psychrometrics** is the science of moist air properties and processes, which is used to illustrate and analyze air-conditioning cycles.
- **It translates** the knowledge of heating or cooling loads (which are in **kW or tons**) into volume flow rates (in **m^3/s or cfm**) for the air to be circulated into the duct.
- **It helps** in quantifying and understanding air conditioning process.
- Amount of **moisture** that the air can carry **increases with its temperature.**

4.2 Psychrometrics and Air-Conditioning Processes

Psychrometric Chart



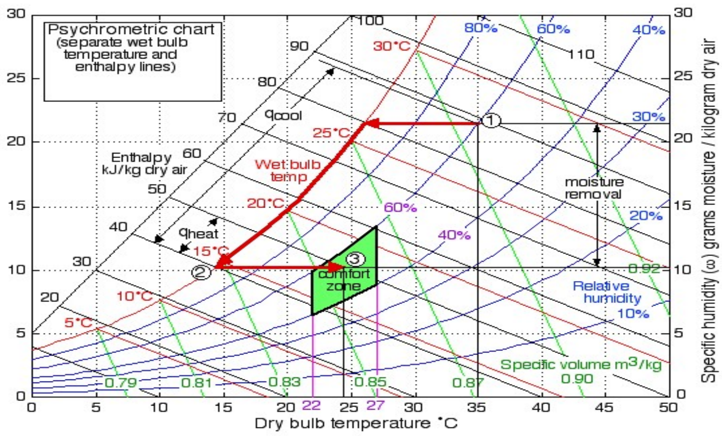
Example: Assume that the outside air temperature is 32°C with a relative humidity of ϕ = 60%. Use the psychrometric chart to determine the air properties? Fig

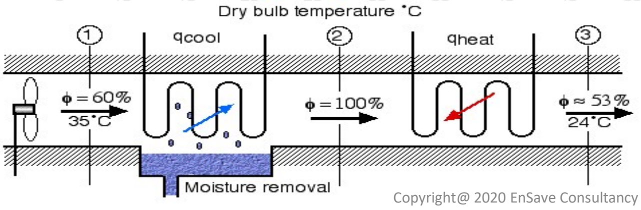
Solution

Specific humidity ω =18 gm-moisture/kg-air
Enthalpy h = 78 kJ/kg-air
Wet-bulb temperature T_{wb} = 25.5°C
Dew-point temperature T_{dp} = 23°C
Specific volume of the dry air v= 0.89m³/kg

If two parameters known, (Td,RH) other Five parameters can be found out

What is a Comfort Zone? How to attain it?





- Most humans feel comfortable when the temperature is between **22°C and 27°C**, and the RH between **40% and 60%.**
- we **either heat or cool, add moisture or dehumidify** as required in order to bring the air into the comfort zone.

Example 2: Outside air at 35°C and 60% RH is to be conditioned by cooling and re-heating with the exit temperature of 24°C and 53% RH. Using the chart estimate (a) the amount of moisture removed, (b) the heat removed, and (c) the amount of heat added.

Ans:
Amount of moisture removed = **11.5g -H_2O** /kg-dry-air
Heat removed = (1)-(2), q_{cool} = **48 kJ/kg** -dry-air
Amount of heat added = (2)-(3), q_{heat} = **10 kJ**/kg-dry-air

Applications of Air-Conditioning and Refrigeration Systems

Air-Conditioning Systems

- Air Conditioning (*for comfort/machine*)
- Split air conditioners
- Fan coil units in a larger system
- Air handling units in a larger system

An industry may also have two or three levels of refrigeration & air conditioning such as:

- Comfort air conditioning (20 – 25 ^{0}C)
- Chilled water system (8 – 10 ^{0}C)
- Brine system (sub-zero applications)

Two principle types of refrigeration:

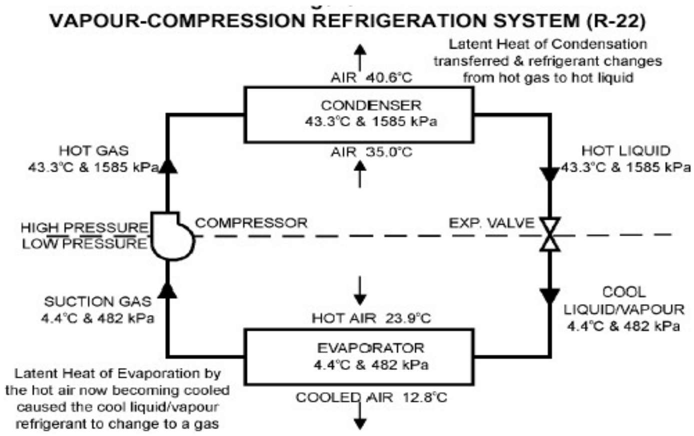
- Vapour Compression Refrigeration (VCR) and
- Vapour Absorption Refrigeration (VAR).

Refrigeration Systems (for processes)

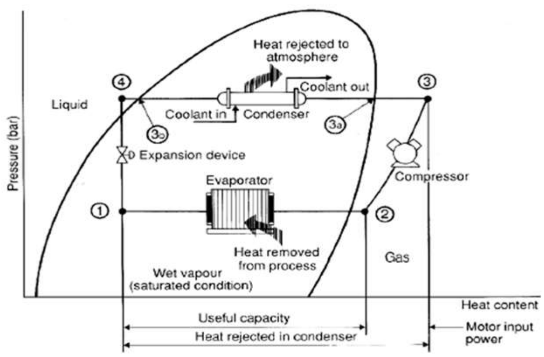
Small capacity units of direct expansion type similar to domestic refrigerators.

- **Centralized chilled water plants** with chilled water as a secondary coolant for temp. **range over 5 ^{0}C**. They can also be used for ice bank formation.
- **Brine plants**, which use brines as lower temp., secondary coolant, **for sub zero temperature** applications (modular unit as well as large centralized plant)
- Plant capacities upto 50 TR are considered as small capacity, 50 – 250 TR as medium capacity and over 250 TR as large capacity units.

4.3 Types of Refrigeration System

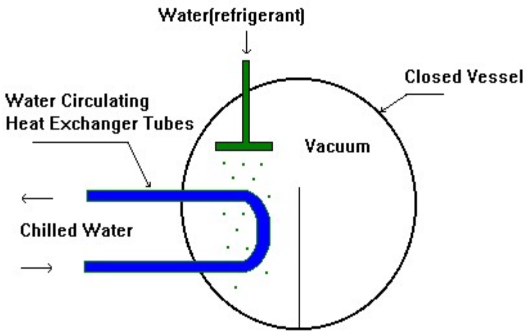


Vapour Compression System

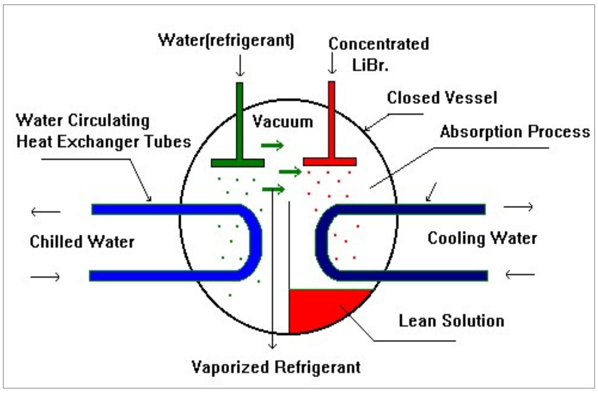


Absorption Refrigeration

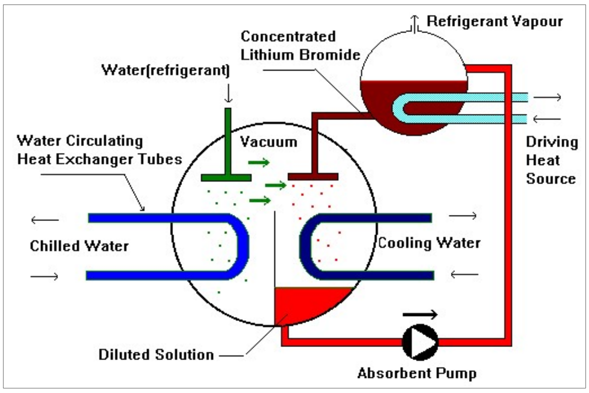
- Absorption chiller is a machine, which produces chilled water by using heat such as steam, hot water, gas, oil etc.
- Chilled water is produced by the principle that liquid (refrigerant), which evaporates at low temperature, absorbs heat from surrounding when it evaporates.
- **Pure water** is used as refrigerant and lithium bromide solution is used as absorbent
- Heat for the vapour absorption refrigeration system can be provided by waste heat extracted from process, diesel generator sets etc. Absorption systems require electricity to run pumps only.
- Depending on the temperature required and the power cost, it may even by economical to generate heat / steam to operate the absorption system.



1. Boiling point of the water is a function of pressure. At atmospheric pressure water boils at 100 deg. C. When maintained at high vacuum, water will boil and subcool itself. The boiling point of the water at 6 mmHg (abs) is 3.7 deg. C.



2. Lithium Bromide (LiBr) has the property to absorb water due to its chemical affinity. At higher concentration and lower temperature LiBr absorbs water vapour (refrigerant vapour) very effectively.



3. As Lithium Bromide becomes dilute it loses its capacity to absorb water vapour. It thus needs to be reconcentrated using a heat source. Heat source may be Steam or Flue gases or even Hot water.

4.5 Compressor Types and Application

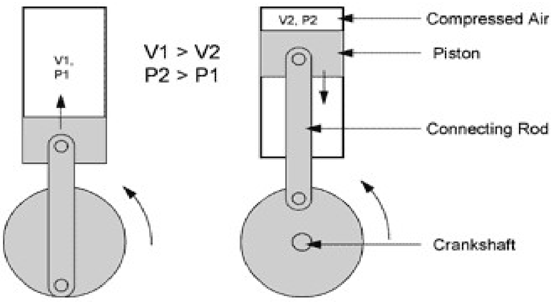
Centrifugal Compressors: Capacity control

- It is most efficient type when operating near full load and able to use a wide range of refrigerants efficientl

1. **Throttling** Centrifugal compressors are the most efficient type when operating near full load. It has a single major moving part - an impeller that compresses the refrigerant gas by centrifugal force. This method of Throttling with inlet guide vanes can vary the load up to 50% below which efficiency decreases rapidly.
2. **Hot gas bypass control.** Older centrifugal machines are not able to reduce load much below 50% due to "surge" in the impeller. As the flow through the impeller is choked off, flow drops abruptly and an oscillation begins as the gas *flutters* back and forth in the impeller resulting vibration. To overcome this older machines deal with low loads by creating a false load by using hot gas bypass.
3. **Variable-speed drives** can reduce the capacity up to 205 load .Below the minimum load provided by the variable-speed drive, inlet guide vanes are used to provide further capacity reduction.

Reciprocating Compressors

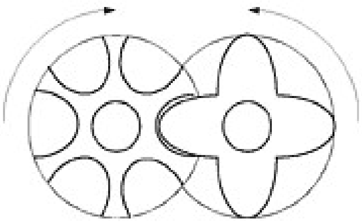
- **Reciprocating Compressors:**
- Maximum efficiency lower than that of centrifugal and screw compressors.
- Efficiency is reduced by clearance volume throttling losses at the intake and discharge valves, abrupt changes in gas flow, and friction
- Part load efficiency very high
- **Capacity Control** Larger multi-cylinder reciprocating compressors commonly reduce output by disabling ("unloading") individual cylinders.
- "suction cutoff." method It is blocking gas flow to the unloaded cylinders
- Variable-speed drives can be used with reciprocating compressors. This method is gaining popularity with the drastic reduction in costs of variable speed drives.



Screw Compressors

Feature: Screw compressors, sometimes called "helical rotary" compressors, compress refrigerant by trapping it in the "threads" of a rotating screw-shaped rotor

- Screw compressors have increasingly taken over from reciprocating compressors of medium sizes and large sizes,
- Screw compressors are applicable to refrigerants that have higher condensing pressures, such as HCFC-22 and ammonia.



Screw Compressors: Capacity Control

- Most common is a **slide valve** that forms a portion of the housing that surrounds the screws.
- **Using a variable-speed drive** for capacity control is limited to oil-injected compressors, because slowing the speed of a dry compressor would allow excessive internal leakage.
- **suction throttling** inherently less efficient than the previous two

Scroll Compressors

- The gas is compressed between two scroll-shaped vanes.
- One of the vanes is fixed, and the other moves within it.
- The moving vane does not rotate, but its center revolves with respect to the center of the fixed vane
- This motion squeezes the refrigerant gas along a spiral path, from the outside of the vanes toward the center, where the discharge port is located.
- The compressor has only two moving parts, the moving vane and a shaft with an off-center crank to drive the moving vane.
- Scroll compressors have only recently become practical, because close machining tolerances are needed to prevent leakage between the vanes, and between the vanes and the casing.

4.7 Performance Assessment of Refrigeration Plants

- The specific power consumption kW/TR is a useful indicator of the performance.
- By measuring refrigeration duty in TR & KW inputs, kW/TR is derived.

The refrigeration TR is assessed as

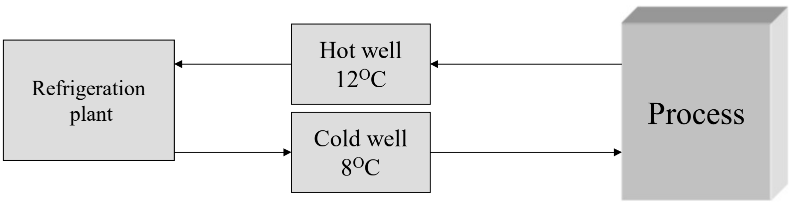
$$\mathbf{TR = Q \cdot C_p \cdot (T_i - T_o) / 3024}$$

Where
TR- is cooling TR duty
Q - is mass flow rate of coolant in kg/hr
C_p - is coolant specific heat in kCal /kg / ^{0}C
T_i - is inlet. Temperature of coolant to evaporator (chiller) in ^{0}C.
T_{o-} is outlet temperature of coolant from evaporator (chiller) in ^{0}C.

Overall energy consumption

- Compressor kW
- Chilled water pump kW
- Condenser water pump kW
- Cooling tower fan kW
- Overall kW/TR = sum of all above kW/ TR

Calculating the operating load of a chiller plant



Chilled water flow – 100 m^3/hr

$$\text{Refrigeration TR -} \quad \frac{\overset{m}{100{,}000\ \text{kg/hr}} \times \overset{C_p}{1} \times \overset{\Delta T}{4}}{3000}$$

$$- \quad 133.33\ \text{TR}$$

$$\text{Efficiency} \quad - \quad \frac{\text{Power drawn by compressor, kW}}{\text{TR}}$$

$$- \quad \frac{120}{133.33} = 0.9$$

Theoretical Coefficient of Performance

Theoretical Coefficient of Performance (Carnot), COP_{Carnot} - a standard measure of refrigeration efficiency of an ideal refrigeration system

It depends evaporator temperature T_e & condenser temperature T_c with COP being given as:

$$COP_{Carnot} = T_e / (T_c - T_e)$$

$$COP = \frac{\text{Cooling effect (kW)}}{\text{Power input to compressor (kW)}}$$

Higher COP_{Carnot} is achieved with higher evaporator temperature and lower condenser temperature.

But COP_{Carnot} is only a ratio of temperatures, and does not take into account compressor type. Hence COP normally used in the industry is given by

Performance Assessment: Air conditioning

- In case of air conditioning units, the airflow at the Fan Coil Units (FCU) or the Air Handling Units (AHU) can be measured with an anemometer.
- Dry bulb and wet bulb temperatures are measured at the inlet and outlet of AHU or the FCU and the refrigeration load in TR is assessed as ;

$$TR = \frac{Q \times \rho \times (h_{in} - h_{out})}{3024}$$

Where, Q is the air flow in m^3/h

ρ is density of air kg/m^3

h_{in} is enthalpy of inlet air kcal/kg

h_{out} is enthalpy of outlet air kcal/kg

- Use psychometric charts to calculate h_{in} and h_{out} from dry bulb/wet bulb temperature which are measured, during trials, by a whirling psychrometer.
- Power measurements at **compressor, pumps, AHU fans, cooling tower fans** can be done by a power analyzer.
- Determine air conditioning load by calculating various heat loads, sensible and latent based on inlet and outlet air parameters, air ingress factors, air flow, no. of people and type of materials stored.
- Indicative TR load for air conditioning as follows

4.8 Factors affecting Performance & energy efficiency of Refrigeration Plants

Effect of Variation in Evaporator Temperature on Compressor Power Consumption

Evaporator Temperature (⁰C)	Refrigeration Capacity (tons)	Specific Power Consumption	Increase in kW/ton (%)
5.0	67.58	0.81	-
0.0	56.07	0.94	16.0
-5.0	45.98	1.08	33.0
-10.0	37.20	1.25	54.0
-20.0	23.12	1.67	106.0

Effect of Variation in Condenser Temperature on Compressor Power Consumption

Condensing Temperature (⁰C)	Refrigeration Capacity (tons)	Specific Power Consumption	Increase in kW/TR (%)
26.7	31.5	1.17	-
35.0	21.4	1.27	8.5
40.0	20.0	1.41	20.5

A 1^0C raise in evaporator temperature can help to save almost 3 % on power consumption.

Effect of Poor Maintenance on Compressor Power Consumption

Condition	Evap. Temp (⁰C)	Cond. Temp (⁰C)	Refrigeration Capacity (tons)	Specific Power Consumption (kW/ton)	Increase in kW/Ton (%)
Normal	7.2	40.5	17.0	0.69	-
Dirty condenser	7.2	46.1	15.6	0.84	20.4
Dirty evaporator	1.7	40.5	13.8	0.82	18.3
Dirty condenser and evaporator	1.7	46.1	12.7	0.96	38.7

4.8 Factors Affecting Performance & Energy Efficiency of Refrigeration Plants

Multi-Staging for Efficiency

- For low temperature applications involving high compression ratios, and for wide temperature requirements, it is economical to employ multi-stage reciprocating machines or centrifugal / screw compressors.

Matching Capacity to System Load

- Part-load operation is important, as most refrigeration applications have varying loads.

Capacity Control and Energy Efficiency

- Reciprocating compressors through cylinder unloading(step-by-step) modulation)
- continuous capacity modulation of centrifugal **through vane control**
- Screw compressors **through sliding valves.**

Multi-level Refrigeration for Plant Needs

- For diverse applications requiring a wide range of temperatures, it is generally more economical to provide several packaged units (several units distributed throughout the plant) instead of one large central plant.

Chilled Water Storage

- Depends on the nature of the load, it is economical to provide a **chilled water storage** facility

4.9 Performance Assessment of window, split and package air conditioning units

Performance Assessment of Package Air Conditioner – Example

- Air conditioner capacity - 10 TR
- Average Air Velocity -2.27 m/s
- Cross Sectional Area -0.58 m^2
- Air Flow Rate -1.32 m^3/sec
- - 4751 m^3/hr

Inlet Air Condition

- DBT -20 °C
- WBT -14 °C
- Sp.Vol -0.8405 m^3/kg
- Enthalpy -9.37 kCal/kg

Outlet Air Condition

- DBT -12.7 °C
- WBT -11.3 °C
- Enthalpy -7.45 kCal/kg
- Cooling Effect *Delivered* =**3.6 TR=12.7 kW**

Energy Efficiency Ratio (EER):

EER is calculated by dividing a chiller's cooling capacity (in watts) by its power input (in watts) at full-load conditions.

EER = Refrigeration effect in watts/ Power input in watts

Power Drawn

- Compressor-4.71 kW
  -4.3 kW (4.71x0.9 eff.)
- Pump - 2.14 kW
- C.T Fan - 0.384 kW

Specific Energy Consumption

- Compressor- 1.31 kW/TR
- Overall - 2 kW/TR
- EER - 12700/4300
  - **2.95 W/W**

4.10 Cold Storage Systems

A **Refrigerated storage** which includes **cold storage** and **frozen food storage** is the best known method of **preservation of food to retain its value and flavor.**

- Equipment's includes compressor, condenser, receiver, air cooling units and associate piping and controls.
- refrigerants used in small unis - HCFC-22, HFC-134a -
- large central plant use ammonia as the refrigerant.

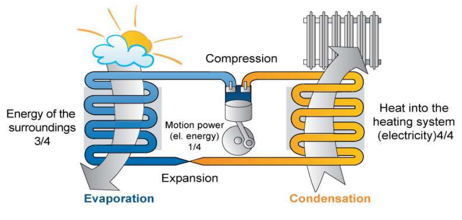
Energy Saving Opportunities in Cold Storage

- **Cold Store Building Design:** Proper orientation, compact chambers, shading of exposed walls, adequate insulation etc. are the important factors.
- **Refrigeration System: S**ystem must be designed for optimum operating conditions like evaporating and condensing temperatures which are direct bearing on energy consumption.
- **Control System**: Proper control for refrigerant level, room temperature, compressor capacity etc., are required to further optimize energy consumption.
- **Air Curtain or Strip Curtain**: The use of air curtains and strip curtains is a common feature to reduce air infiltration due to frequent/long door openings. Fan operated air curtains are expensive and work on electrical power whereas strip curtains are cheaper
- **Heat Recovery System**: WHR Can be installed to recover a part of the heat rejected by the refrigeration for generating hot water.

4.11 Heat Pumps and Their Applications

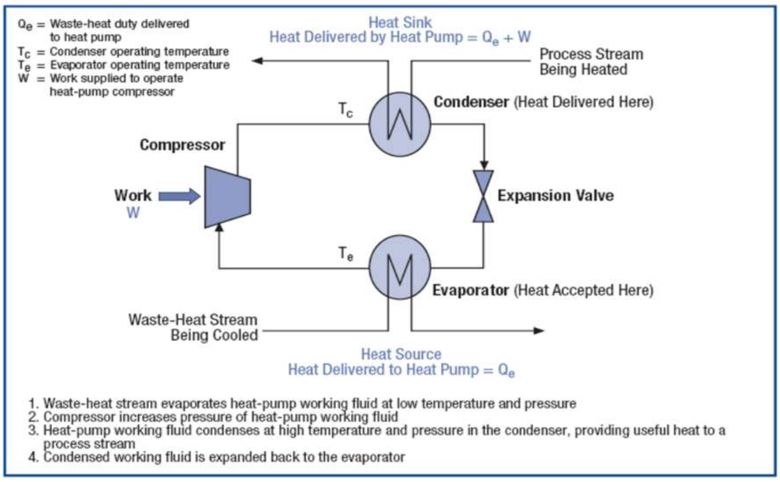
Heat Pump Technology

- A heat pump is same as an air conditioner except that the heat rejected in an air conditioner becomes the useful heat output.
- Heat flows naturally from a higher to a lower temperature.
- Heat pumps are able to force the heat flow in the other direction, using small amount of high quality drive energy (electricity, fuel, or high-temp. waste heat).



Heat Pump

Principle of operation of Heat Pump



List down the Heat Pump Applications

Industrial heat pumps are mainly used for:

- Space heating:
- Heating of process streams;
- Water heating for washing, sanitation and cleaning;
- Steam production;
- Drying/dehumidification;
- Evaporation;
- Distillation;
- Concentration.

When heat pumps are used in drying, evaporation and distillation processes, heat is recycled within the process.

For space heating, heating of process streams and steam production, heat pumps utilise (waste) heat sources between 20ºC and 100ºC.

4.12 Ventilation Systems

- Ventilation is nothing but **simple air circulation**
- **Purpose:** The extraction of stale, overheated , contaminated air and supply of fresh air in amounts necessary to provide healthy and comfortable conditions for the occupants of the room.
- Ventilation effectiveness is dictated by **Number of Air Changes per Hour** (**ACH**).

Typical Air Changes per Hour	
Location	**Air changes per hour**
Boiler room	15 – 30
Compressor room	**10** – 12
Conference rooms	10 – 20
Engine rooms	15 – 30
Lavatories	6 – 15
Offices	6 – 10
Welding shops	15 – 30

Calculation of ventilation rate:

- If the compressor room size is 15 m (L) x 10 m (B) x 4 m (H)
- then the ventilation rate is = L x B x H x ACH
- = 15 x 10 x 4 x **10** = **6000 m^3/hr**

4.13 Ice Bank Systems

- Ice Bank System is a proven technology that has been utilized **for decades Thermal energy storage takes** advantage of low cost, off-peak electricity, produced more efficiently throughout the night, to create and store cooling energy for use when electricity tariffs are higher, typically during the day.
- The essential element for either full- or partial-storage configurations are **thermal- energy storage tanks**.

How Ice Bank Works?

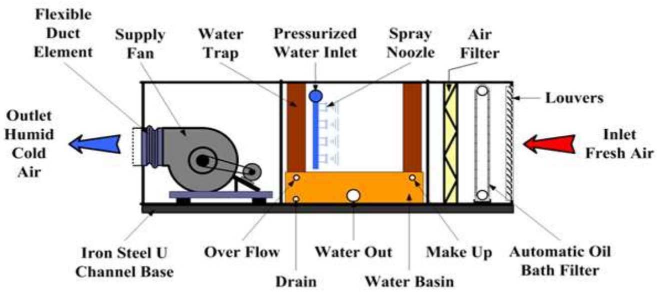
- During off-peak night time hours, the chiller charges/operates the ICEBANK tanks for use during the next day's cooling.

4.14 Humidification Systems

- This is a process involving reduction in dry bulb temperature and increase in specific humidity.
- Example: In textile processing, the properties like dimensions, weight, tensile strength, elastic recovery, electrical resistance, rigidity etc. of all textile fibre are influenced by humidity maintained.
- Temperature does not have a great effect on the fibres **but the temperature dictates the amount of moisture the air will hold** in suspension and, therefore, temperature and humidity must be considered together.

If the air washer is ideal, the dry bulb temperature and wet bulb temperature of the air would be equal. Dry bulb temperature of the air goes down in the process and the effect of cooling is due to the evaporation of some part of the water.
That is why it is **called Evaporative Cooling.**

Adiabatic saturation or evaporative cooling



Air Washer Unit

Humidifying Air by adding Water

- If water is added to air without any heat supply the state of air change adiabatic along a constant enthalpy line in the psychrometric chart.
- The dry bulb temperature of the air decreases.
- The amount of added water can be expressed as

$$m_w = v \rho \left(\omega_{out} - \omega_{in}\right)$$

Where,

- m_w = mass of added water (kg/hr)
- v = volume flow of air (m^3/hr)
- ρ = density of air
  - vary with temperature, 1.293 kg/m^3 at 20°C (kg/m^3)

ω = specific humidity of air (kg/kg)

Example - Humidifying Air by adding Water

In an air washer of textile humidification ,airflow of 3000 m3/h at 25°C and 10% RH is humidified to 60% RH by adding water through spray nozzles. Calculate the amount of water required.
The specific humidity of air at inlet and outlet are 0.002 kg/kg and 0.0062 kg/kg respectively.

Solution

The amount of water added can be calculated:

$$m_w = 3000 \times 1.184 \times (0.0062\ 0.002)$$
$$= 14.9 \text{ kg/h}$$

4.15 Standards and Labeling of Room Air Conditioners

Standard specifies the energy labeling requirements **for single-phase split and unitary air conditioners** of the vapour compression type for **household use** up to a rated cooling capacity of 11 kW and that fall within the scope of IS1391 Part 1 and Part 2, **being manufactured, imported, or sold in India.**

The Table 4.8 & 4.9 below is **valid for** split and unitary type air conditioners between 01 January 2014 and **31st December 2015**. ?

Table : Star Rating Band valid for **Split type air conditioners** (from 01 January 2014 to 31 December 2015)

Star Rating	Energy Efficiency Ratio (Watt/Watt)	
	Minimum	Maximum
1 Star *	2.70	2.89
2 Star * *	2.90	3.09
3 Star * * *	3.10	3.29
4 Star * * * *	3.30	3.49
5 Star * * * * *	3.50	

Table : Star Rating Band valid **for Unitary type air conditioners** (from 01 January 2014 to 31 December 2015)

Star Rating	Energy Efficiency Ratio (Watt/Watt)	
	Minimum	Maximum
1 Star *	2.50	2.69
2 Star * *	2.70	2.89
3 Star * * *	2.90	3.09
4 Star * * * *	3.10	3.29
5 Star * * * * *	3.30	

4.16 ENERGY SAVINGS OPPORTUNITIES

- **Cold Insulation**
- **Building Envelope**
- **Building Heat Loads Minimisation**
- **Process Heat Loads Minimisation**

  Minimize both TR and temperature level by
  - Flow optimization and
  - Heat transfer area increase to accept higher temperature coolant
  - Avoiding wastages like heat gains, loss of chilled water, idle flows
  - Frequent cleaning / de-scaling of all heat exchangers

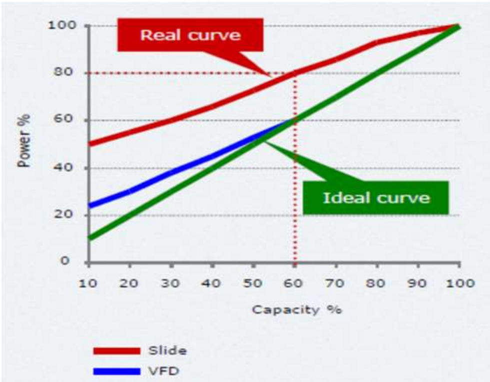
4.17 Case Study: Screw Compressor Application

Use of VFD for screw compressor motor in brewery plant

The screw compressor is part of the refrigeration system which uses ammonia gas as the refrigerant for producing chilled water. The drive motor for the compressor has the following nameplate data:

- Capacity -315KW.
- Supply Voltage - 415V, 3Φ, 50Hz.
- Design Speed - 3000RPM.
- Full Load Current (FLC) - 620A.

Trials were conducted with a VFD suitable for the above-mentioned motor. For the purpose of comparison, readings were taken for both cases-compressor running **with slide valve capacity control, and control with VFD.**
Figure shows the typical power consumption variation with load with and without VFD.



Note:. Typically, 60% capacity requires 80% power.

How to find KW/TR & EER ?

Solved Example:

Measured values of a 20 TR package air conditioning plant are given below:
Average air velocity across suction side filter: 2.5 m/s
Cross Sectional area of suction: 1.2 m^2
Inlet air = Dry Bulb:20°C, Wet Bulb= 14 °C, Enthalpy= 9.37 kcal/kg
Outlet air =Dry Bulb: 12.7 °C, Wet Bulb: 11.3 °C; Enthalpy: 7.45 kcal/kg
Specific volume of air: 0.85 m^3/kg
Power drawn: by compressor: 10.69 kW
by Pump: 4.86 kW
by Cooling tower fan: 0.87 kW

Calculate:

a) Air Flow rate in m^3/hr
b) Cooling effect delivered in kW
c) Specific power consumption of compressor in kW/TR
d) Overall kW/TR
e) Energy Efficiency Ratio in kW/kW

Ans:

a) Air flow rate = 2.5x1.2 = 3 m^3/sec = 10800 m^3/hr
b) Cooling Effect delivered
= [(9.37-7.45)x10800]/(0.85x3024)
= 8.07 TR = 28.32 kW
a) Compressor kW/TR = 10.69/8.07 = 1.32
b) Overall kW/TR = (10.69+4.86+0.87)/8.07 = 2.04
c) Energy Efficiency Ratio(EER) in kW/kW
= 28.32/10.69 = 2.65

QUESTIONS	
Objective Type Questions	
1.	Higher COP can be achieved with______. a) lower evaporator temperature and higher condenser temperature b) higher evaporator temperature and lower condenser temperature c) higher evaporator temperature and higher condenser temperature d) lower evaporator temperature and lower condenser temperature
2.	Li – Br water absorption refrigeration systems have a COP in the range of a) 0.4 – 0.5 b) 0.65 – 0.70 c) 0.75 – 0.80 d) none of the above
3.	**Hermetic system are used in** a) domestic refrigerators b) centrifugal chillers c) screw chillers d) large reciprocating chillers
4.	**Which of the following can be used as refrigeration both in vapour compressor and vapour absorption system** a) ammonia b) R –11 c) R-12 d) lithium Bromide
5.	One ton of refrigeration (TR) is equal to a) 3.51 kW b) 3024 kcal/hr c) 12,000 BTU/hr d) all of the above

Thank You

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