CENTRAL AIR-CONDITIONING CHILLER SYSTEMS

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Course Contents

- Introduction
- Types of chillers
- Chiller efficiency & lifecycle cost
- Chiller configuration
- Consolidation of chiller systems
- Chilled water and condenser water temperature reset
- Economisers
- Thermal storage systems

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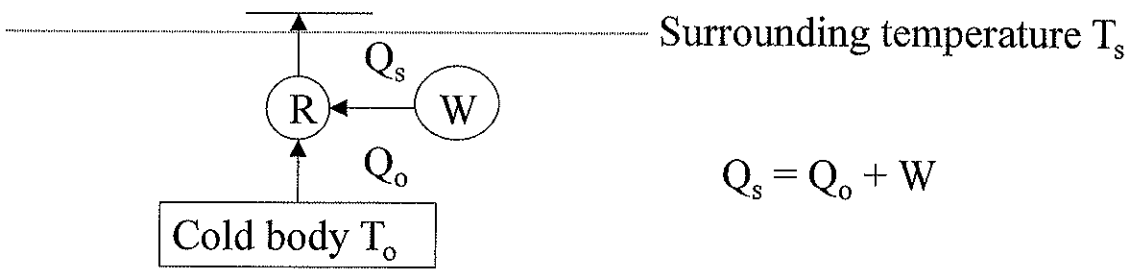
Overview of air-conditioning

- In air-conditioning we need to remove heat from the occupied space which should be maintained at about 23°C to 24°C
- Since heat flows from higher to lower temperature, the fluid removing heat has to be colder than the space temperature
- Once the heat is removed, it has to be rejected to something that is colder
- This requires refrigerating systems which can maintain a body at a temperature below that of the surroundings

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Refrigeration system

- In a refrigerating machine, R absorbs heat from the cold body at temperature T_o and rejects the heat Q_s to the surroundings at temperature T_s.
- This process requires work W to be done on the system



- The heat rejected to the surroundings equals the heat absorbed from the cold body plus the work done or mechanical energy consumed

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Refrigeration cycle

- Refrigerants are used in refrigerating machines . Refrigerants evaporate at low temperatures and condense at temperatures higher than ambient temperature
- Therefore, refrigerants can be evaporated at low temperatures during which heat is absorbed and then condensed at a higher temperature and pressure where the absorbed heat (plus that of the work done) is rejected

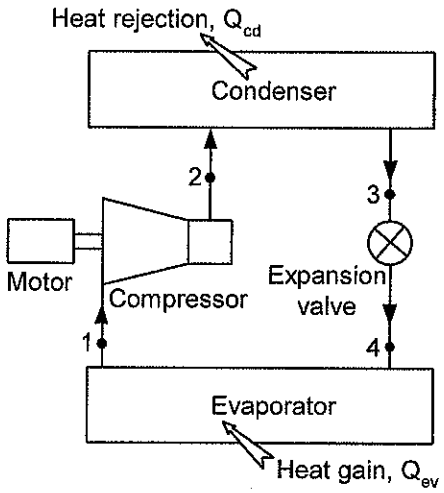
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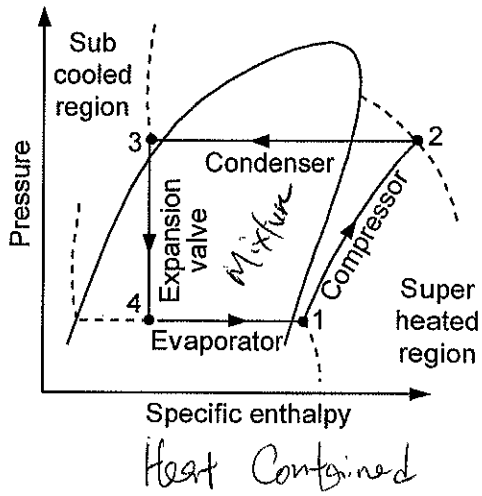
Refrigeration cycle (contd.)

- To enable heat rejection to the surroundings, the refrigerant has to condense at a higher temperature and pressure. Therefore, the pressure of the refrigerant has to be increased by compression using a compressor
- Once the refrigerant is condensed, the pressure has to be lowered back again to enable evaporation at low temperature to absorb heat from the cold object

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Vapour compression cycle





Heat Contained

- This is the principle of the vapour compression cycle
- Cycle has 4 mechanical components through which refrigerant is circulated in a closed loop. The refrigerant is separated from the air or water to be cooled

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Vapour compression cycle (contd.)

- **The refrigerant enters the compressor as low pressure vapour and is compressed to high pressure vapour**
- **The high pressure vapour flows to the condenser which is a heat exchanger where heat is rejected from the refrigerant. The refrigerant condenses from high pressure vapour to high pressure liquid**

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Vapour compression cycle (contd.)

- **The high pressure liquid refrigerant flows through the expansion valve to the evaporator. The high pressure liquid refrigerant becomes low pressure liquid refrigerant**
- **In the evaporator which is a heat exchanger, the liquid refrigerant evaporates at low temperature by absorbing heat from the surroundings. This is the cooling effect of the refrigeration system. The refrigerant becomes low pressure vapour and enters the compressor and the cycle is repeated.**

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Common refrigerants

CFCs:	R11, R12, R113, R114, R115
HCFCs:	R**22**, R123
HFC:	R134a
Blends:	407C, 410A

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Phase out dates

CFCs Already phased out

HCFCs	Developed Countries	Developing Countries
Baseline	1989	2009 / 2010
Freeze	1996	2013
99.5% reduction	2020	2030 (97.5%)
100% reduction	2030	2040

HFCs No phase out date as at present

Blends HCFC blends – same as HCFCs
HFC blends – same as for HFCs

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Important criteria for refrigerant

- **Efficiency**
- **ODP**
- **GWP**
- **Atmospheric life**
- **Toxicity**
- **Cost**
- **Operating pressure**

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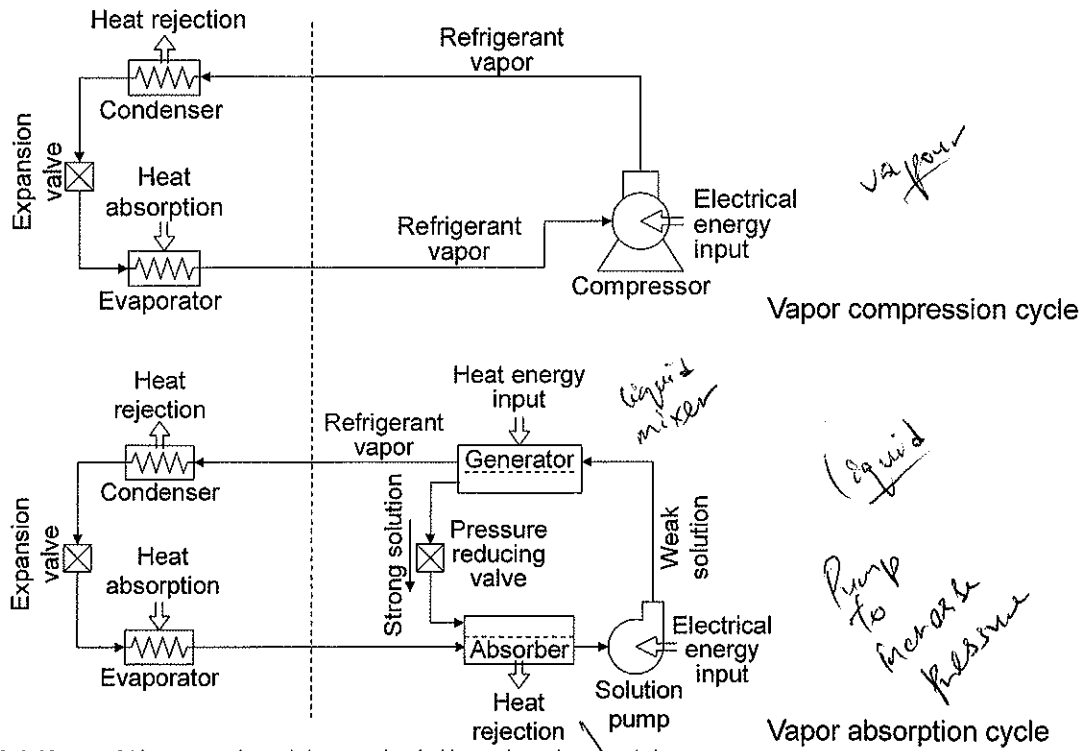
Comparison of refrigerants

Refrigerant	Atmospheric life	ODP	GWP	Theoretical COP
R11	45	1.0	4750	5.02
R123	1.3	0.02	77	4.9
R12	100	1.0	10,900	4.7
R134a	14	0	1430	4.6
R22	12	0.055	1810	4.66
R407C	30	0	1800	4.5
R410A	30	0	2100	4.21

Source: ASHRAE Handbook

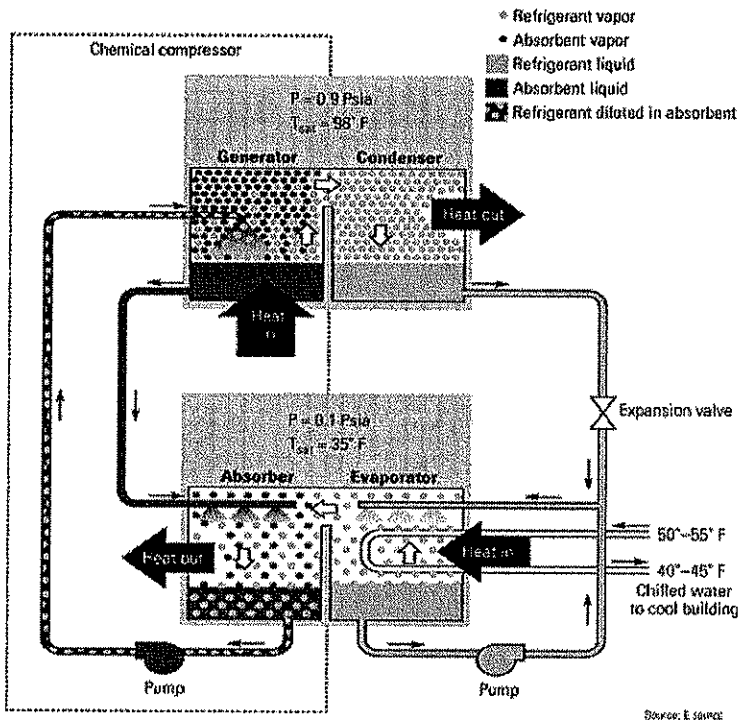
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Absorption cycle



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Absorption cycle



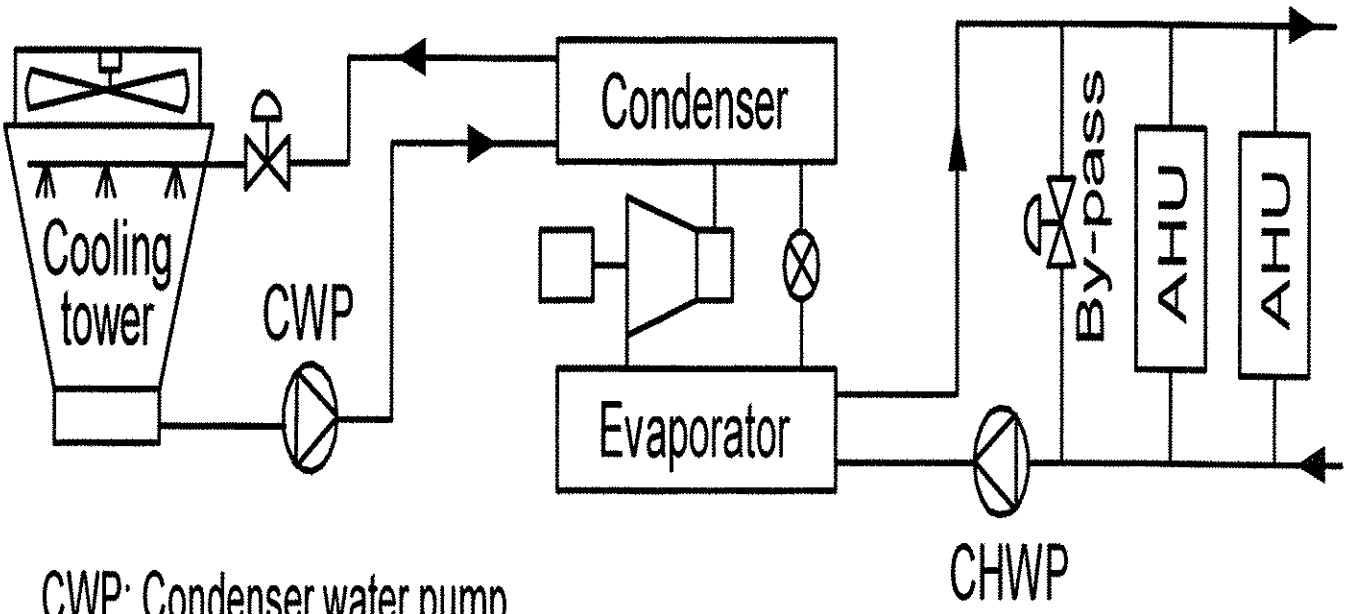
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Types of air conditioning systems

- Window
- Split / VRV
- Package units
- Central systems

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Main Component of Central Air-conditioning System

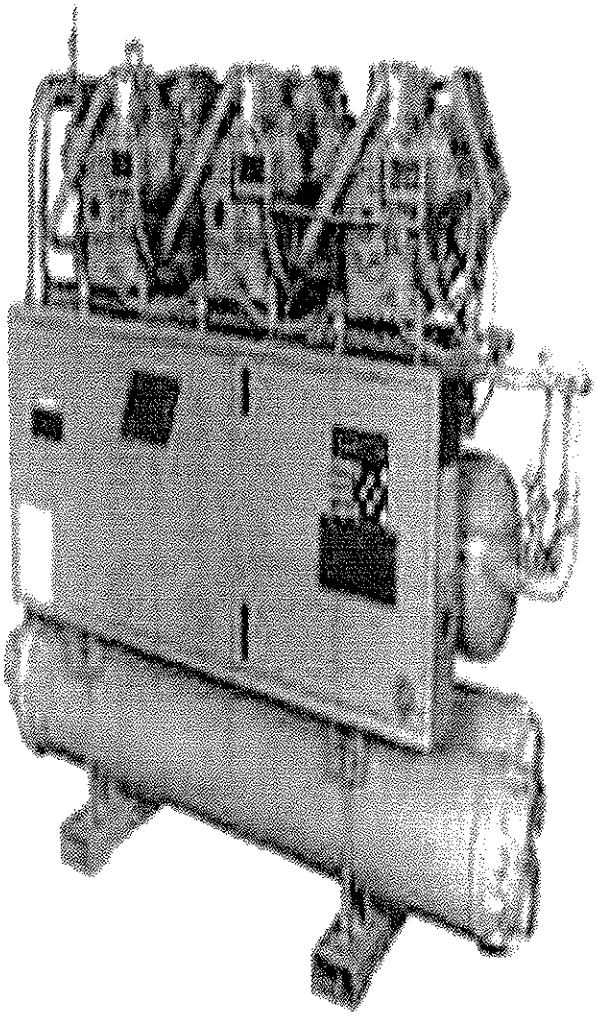


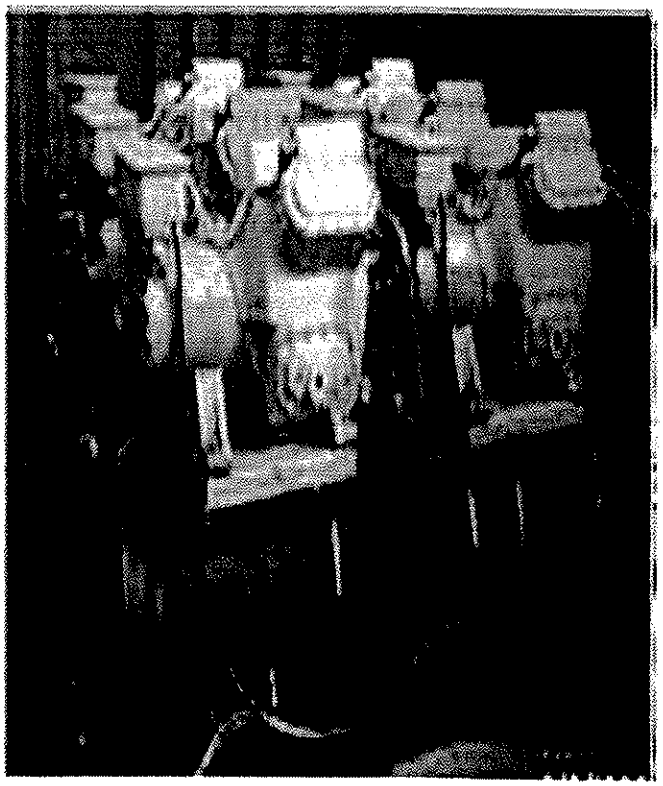
CWP: Condenser water pump

CHWP: Chilled water pump

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Reciprocating chillers





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Scroll compressors



1) Gas enters the outer openings



2) The open passages are sealed off as gas is drawn in.



3) Gas is compressed into two increasingly smaller pockets

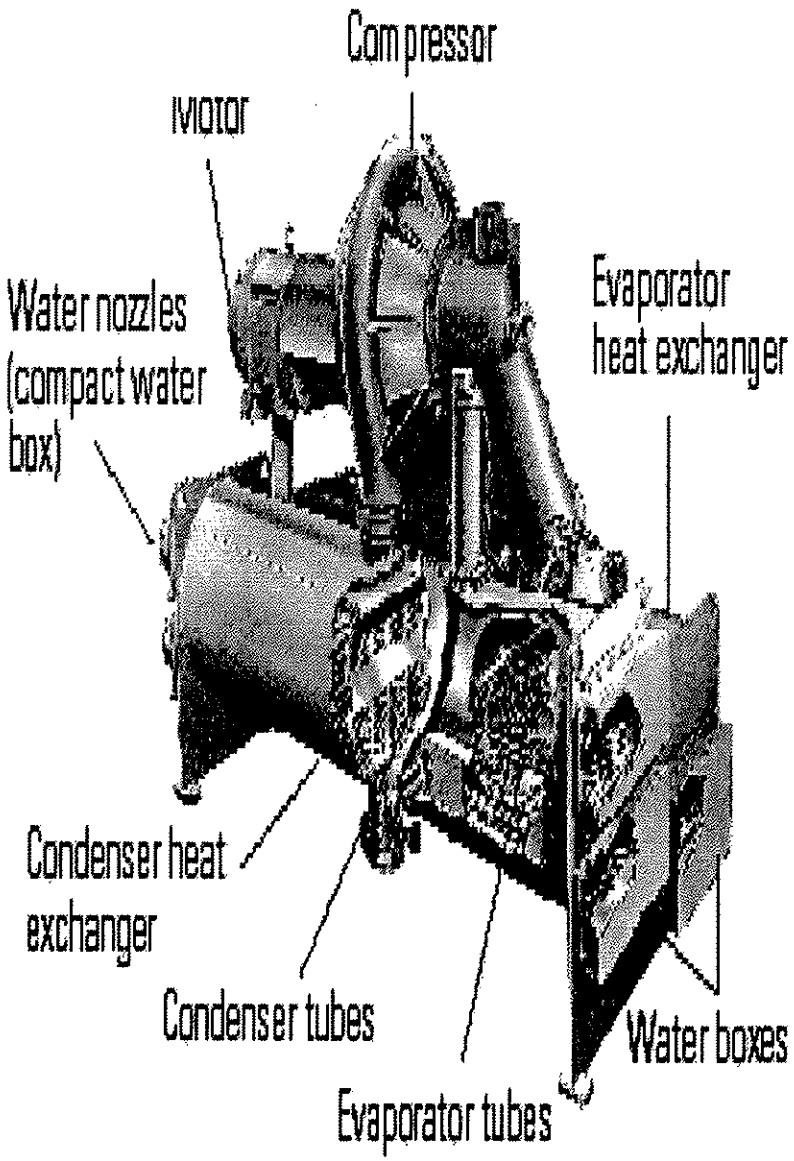


4) Gas is discharged at the centre port

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Centrifugal chillers

Figure 1: Centrifugal chiller cutaway



Source: York International

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Refrigeration Capacity

- The capacity of air-conditioning machines is classified by how many "Tons" of refrigeration (RT) effect it can produce

- 1 RT of refrigeration is based on the amount of cooling 1 ton (2000 lb) of ice can produce by melting over a 24-hour period. 1 RT of refrigeration has the ability to remove 288,000 Btu in a 24-hr period

1 RT = 2000 lb x 144 Btu/lb = 288,000 Btus

Therefore, 1 RT = 12,000 Btu/hr

Also, 1 RT = 3.517 kW

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EER & SEER

EER (energy efficiency ratio) is measured under steady state conditions (specific outdoor temperature)

= cooling capacity in BTUs / input power in Watts

COP = EER x 0.2931

SEER is the seasonal energy efficiency ratio (takes into account part load operation)

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IPLV / NPLV

IPLV or NPLV equation and procedure are intended to provide a consistent method for calculating a single number part-load performance figure of merit for Water-Chilling packages

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Efficiency of chillers

Biggest consumer of electricity in buildings.

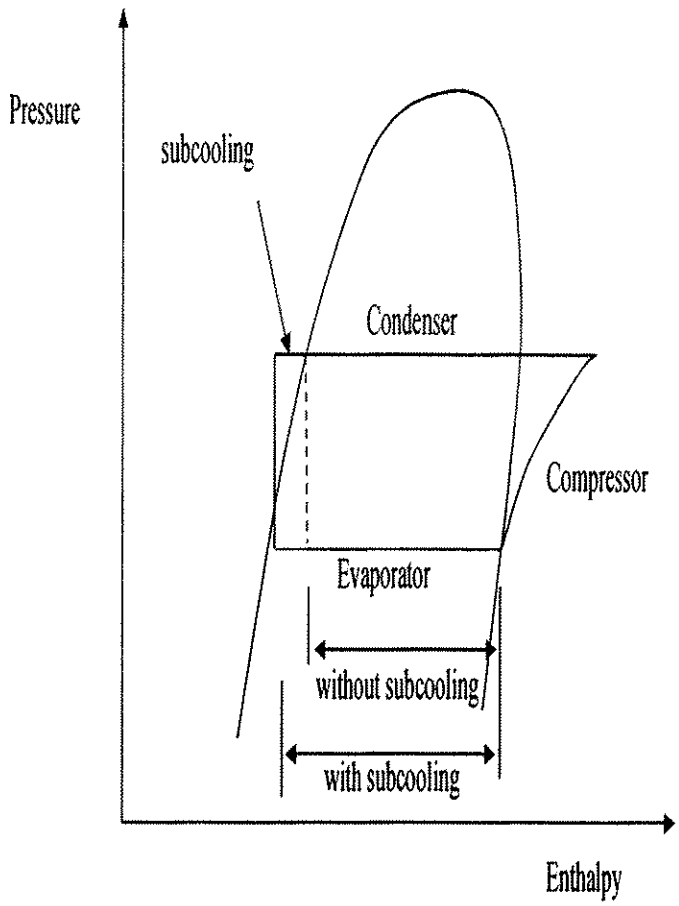
Operating efficiency of chillers depend on :

- type of chiller
- rated efficiency
- part-load performance
- capacity to load match
- chilled water and condenser water temperatures
- condition of condenser tubes

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Subcoolers

Chillers that do not have multi-stage compressors use liquid subcooling to improve the refrigerant effect and therefore the chiller efficiency



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Water cooled vs Air cooled chillers

- Water cooled chillers (WCC) are much more efficient than air cooled chillers (ACC) because the condensing pressure is lower

- Typical efficiency of ACC range from 1.0 to 1.5 kW/RT compared to 0.5 to 0.6 kW/RT for WCC

- Although first cost of WCC systems is higher that ACC systems, the extra initial cost can back in a few years due to the superior energy efficiency of WCC

- However, ACC have many applications because they do not need cooling towers, make-up water flow and plant rooms

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Example (contd.)

[redacted]

The energy savings by replacing these chillers with water cooled chillers is illustrated in the following Table :

Hours of Operation	Number of hours A	Cooling load (RT) B	Present chiller efficiency C	Present kWh consumption A x B x C	Proposed chiller efficiency D	Proposed kWh consumption A x B x D
0800 to 0900	1	200	1.3	260	0.6	120
0900 to 1000	1	200	1.3	260	0.6	120
1000 to 1100	1	225	1.3	293	0.59	133
1100 to 1200	1	225	1.3	293	0.59	133
1200 to 1300	1	250	1.25	313	0.58	145
1300 to 1400	1	300	1.2	360	0.57	171
1400 to 1500	1	250	1.25	313	0.58	145
1500 to 1600	1	250	1.25	313	0.58	145
1600 to 1700	1	250	1.25	313	0.58	145
1700 to 1800	1	200	1.3	260	0.6	120
1800 to 1900	1	200	1.3	260	0.6	120
1900 to 2000	1	200	1.3	260	0.6	120
2000 to 2100	1	150	1.4	210	0.62	93
2100 to 2200	1	150	1.4	210	0.62	93
				3915		1803

Savings = (3915 – 1803) = 2112 kWh/day

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Example (contd.)

Hours of Operation	Number of hours	Cooling load (RT)	Consumption for pumps & cooling towers (kWh)	Make-up water consumption (m^3)
	A	B	A x B x 0.15 kW/RT	B x (1.02×10^{-2})
0800 to 0900	1	200	30	2.04
0900 to 1000	1	200	30	2.04
1000 to 1100	1	225	34	2.30
1100 to 1200	1	225	34	2.30
1200 to 1300	1	250	38	2.55
1300 to 1400	1	300	45	3.06
1400 to 1500	1	250	38	2.55
1500 to 1600	1	250	38	2.55
1600 to 1700	1	250	38	2.55
1700 to 1800	1	200	30	2.04
1800 to 1900	1	200	30	2.04
1900 to 2000	1	200	30	2.04
2000 to 2100	1	150	23	1.53
2100 to 2200	1	150	23	1.53
			458	31.11

Extra electrical energy used = 458 kWh/day

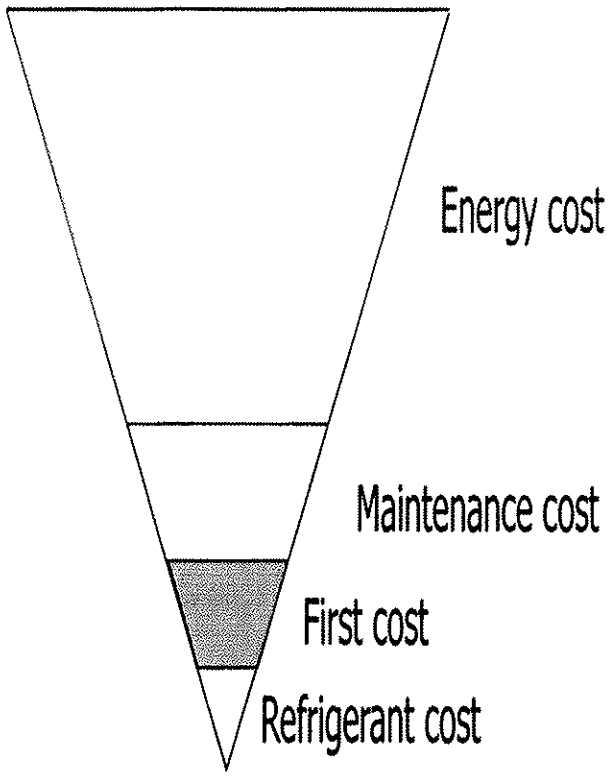
Therefore, the net kWh savings = (2112 – 458) = 1654 kWh/day.

Water usage = 31.11 m^3/day

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Chiller efficiency & life cycle cost

- high efficiency chillers - 0.5 to 0.55 kW/RT
- higher first cost
- running cost exceeds the first cost by 10 to 15 times over the operating life



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Example – chiller efficiency

Example

Consider the case of three 500RT capacity chillers:

Chiller	First cost	Efficiency (kW/RT)
1	$300,000	0.5
2	$275,000	0.55
3	$250,000	0.65

Compute the life cycle cost for a 10 year period based on the following:

Chiller is to operate 10 hrs/day, 250 days a year

Electricity tariff = $0.10 / kWh

Electricity cost escalation is 2% a year

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Example (contd.)

[redacted]

The annual life cycle cost comparison for the three chiller combinations is given in the Table

	Annual cost for chillers		
	0.5 kW/RT	0.55 kW/RT	0.65 kW/RT
Year 0	$ 300,000	$ 275,000	$ 250,000
Year 1	$ 62,500	$ 68,750	$ 81,250
Year 2	$ 63,750	$ 70,125	$ 82,875
Year 3	$ 65,025	$ 71,528	$ 84,533
Year 4	$ 66,326	$ 72,958	$ 86,223
Year 5	$ 67,652	$ 74,417	$ 87,948
Year 6	$ 69,005	$ 75,906	$ 89,707
Year 7	$ 70,385	$ 77,424	$ 91,501
Year 8	$ 71,793	$ 78,972	$ 93,331
Year 9	$ 73,229	$ 80,552	$ 95,197
Year 10	$ 74,693	$ 82,163	$ 97,101
Total	$ 984,358	$ 1,027,793	$ 1,139,665

(all costs are energy costs except year 0 capital cost)

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Example (contd.)

Assume the following efficiency values at different load conditions for the 0.5 kW/RT chiller (can normally be obtained from chiller suppliers)

Chiller load	Loading %	Efficiency
500	100%	0.5
450	90%	0.52
400	80%	0.55
350	70%	0.59
300	60%	0.6
250	50%	0.67

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Example (contd.)

[redacted]

If the building operates 250 days/year at the same load profile, the annual electricity cost

= 2258.5 kWh/day x 250 days/year x $0.10/kWh

= $56,463

This can be repeated for the other 2 chillers for year 1

Thereafter, the energy costs for year 1 onwards can be computed using the cost escalation factor

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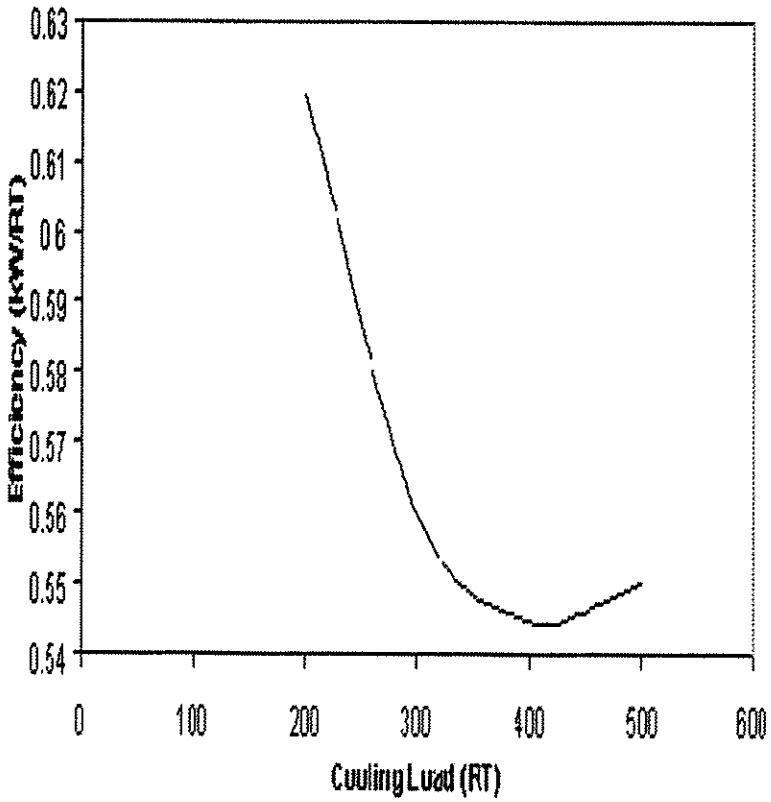
Example (contd.)

Estimated energy cost for 0.55 kW/RT chiller

Time	Cooling Load (RT)	Chiller loading	Chiller efficiency (kW/RT)	kWh consumption
	A		B1	C1=A x B1
0800 - 0900	350	70%	0.64	224
0900 - 1000	375	75%	0.63	236
1000 - 1100	400	80%	0.6	240
1100 - 1200	450	90%	0.57	257
1200 - 1300	500	100%	0.55	275
1300 - 1400	500	100%	0.55	275
1400 - 1500	450	90%	0.57	257
1500 - 1600	400	80%	0.6	240
1600 - 1700	400	80%	0.6	240
1700 - 1800	350	70%	0.64	224
			Total	2467 kWh/day

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Chillers sizing & configuration



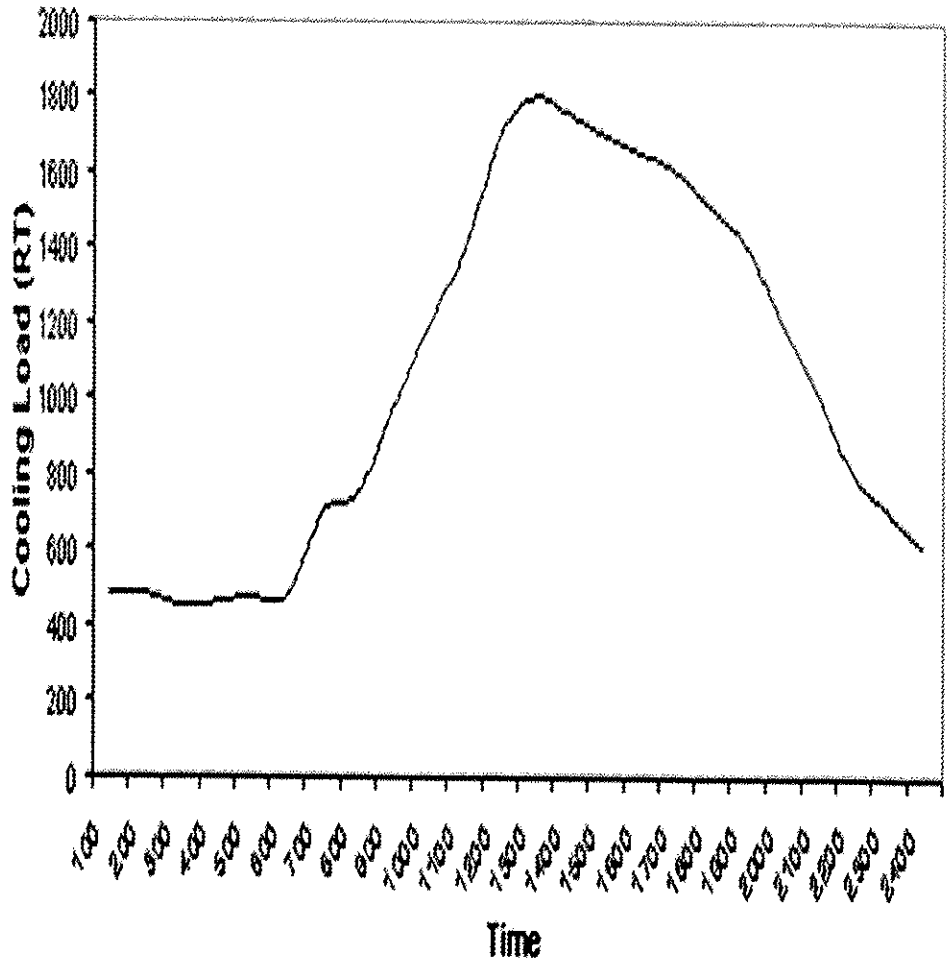
Typical chiller part-load performance

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Example - Chillers sizing & configuration

Example

- Consider building with cooling load profile shown in the Figure



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Example (contd.)

Assuming the part-load performance data for the 1800 RT capacity is as follows:

Percent loading	Cooling capacity (RT)	Efficiency (kW/RT)
100	1800	0.58
90	1620	0.57
80	1440	0.57
70	1260	0.57
60	1080	0.58
50	900	0.60
40	720	0.64
30	540	0.71
20	360	0.91

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Example (contd.)

Assume the part-load data of the 500 RT, 650 RT and 1000 RT chillers is as follows:

Percent loading	Efficiency (kW/RT) 500 RT chiller	Efficiency (kW/RT) 650 RT chiller	Efficiency (kW/RT) 1000 RT chiller
100	0.60	0.59	0.59
90	0.60	0.59	0.58
80	0.60	0.59	0.58
70	0.61	0.60	0.59
60	0.62	0.61	0.60
50	0.65	0.63	0.63
40	0.71	0.68	0.68
30	0.79	0.75	0.75
20	0.98	0.95	0.90

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Example (contd.)

[redacted]

Similarly, the annual energy consumption using 2 x 650 RT and 1 x 500 RT chiller can be estimated as follows:

Time	Load (RT)	Available capacity (RT)	Loading (%)	Average Efficiency (kW/RT)	Hourly power consumption (kW)
0100	480	500	96%	0.60	288
0200	480	500	96%	0.60	288
0300	450	500	90%	0.60	270
0400	460	500	92%	0.60	276
0500	470	500	94%	0.60	282
0600	480	500	96%	0.60	288
0700	700	1150	61%	0.62	434
0800	750	1150	65%	0.61	458
0900	984	1150	86%	0.60	590
1000	1200	1300	92%	0.59	708
1100	1400	1800	78%	0.60	840
1200	1700	1800	94%	0.60	1020
1300	1800	1800	100%	0.60	1080
1400	1750	1800	97%	0.59	1033
1500	1700	1800	94%	0.60	1020
1600	1650	1800	92%	0.59	974
1700	1600	1800	89%	0.59	944
1800	1500	1800	83%	0.60	900
1900	1400	1800	78%	0.60	840
2000	1200	1300	92%	0.59	708
2100	1000	1150	87%	0.60	600
2200	800	1150	70%	0.61	488
2300	700	1150	61%	0.62	434
2400	600	650	92%	0.59	354
				Total	15,116 kWh/day

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Consolidation of chiller plant

Chiller performance can also be improved through consolidation of chiller plant

Some possible candidates :

- tower block and podium blocks having two plants
- different buildings within one facility having different plants (eg. Hotels)
- standalone systems serving specific areas

Larger scale application is District Cooling Systems

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Example (contd.)

Office tower chiller plant operation

Hours of operation	Number of hours	Cooling load (RT)	Chiller loading	Chiller efficiency (kW/RT)	Present kWh consumption
	A	B		C	A x B x C
0800 to 0900	1	500	100%	0.57	285
0900 to 1000	1	500	100%	0.57	285
1000 to 1100	1	550	55%	0.74	407
1100 to 1200	1	600	60%	0.7	420
1200 to 1300	1	650	65%	0.72	468
1300 to 1400	1	600	60%	0.7	420
1400 to 1500	1	600	60%	0.7	420
1500 to 1600	1	550	55%	0.74	407
1600 to 1700	1	500	100%	0.57	285
1700 to 1800	1	500	100%	0.57	285
1800 to 1900	1	350	70%	0.68	238
1900 to 2000	1	150	30%	0.95	142.5
2000 to 2100	1	150	30%	0.95	142.5
2100 to 2200	1	150	30%	0.95	142.5
				Total	4347.5

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Example (contd.)

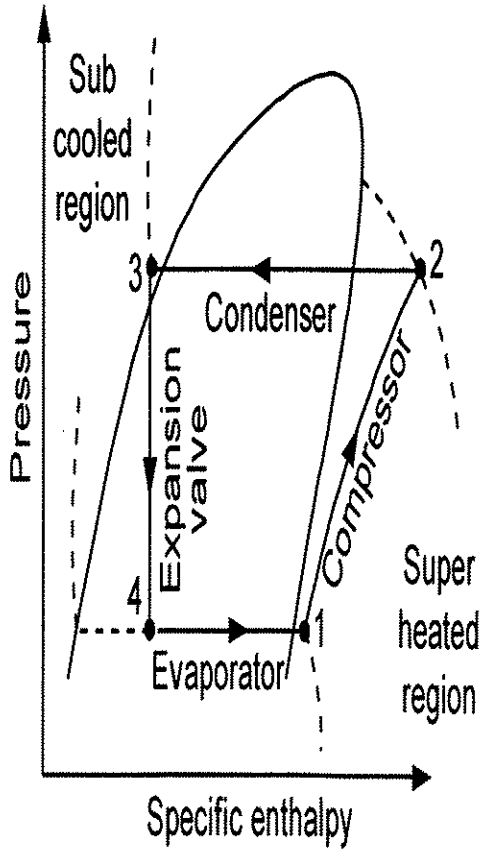
- Consolidated plant can be a completely new plant or one of the existing plants can be used to serve the combined load (with or without additional chillers)
- Need to ensure new system static pressure does not exceed equipment design pressure (use heat exchangers if required)
- In this example, logical choice is to use the office tower plant to serve as the consolidated plant (2 x 500 RT chillers can operate during peak periods and 1 x 500 RT chiller off-peak periods)

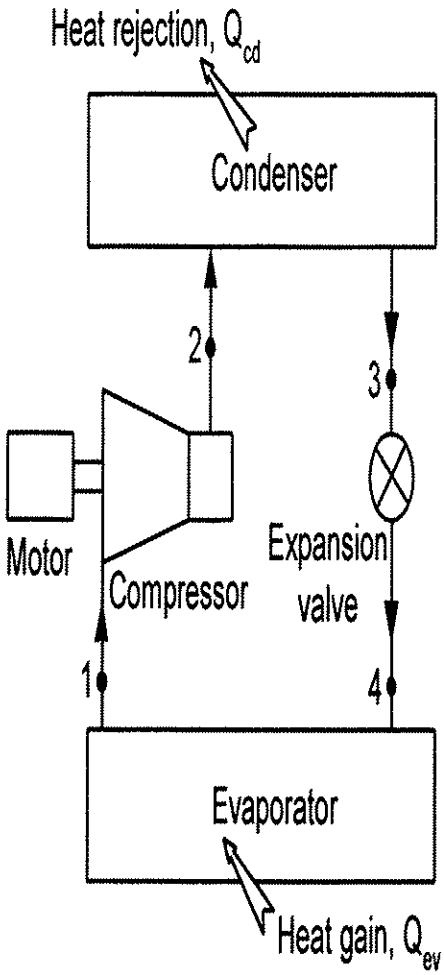
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Chilled water and condenser water reset

Vapour compression cycle -
compressor power can be reduced by

- increasing evaporating pressure
- decreasing condensing pressure

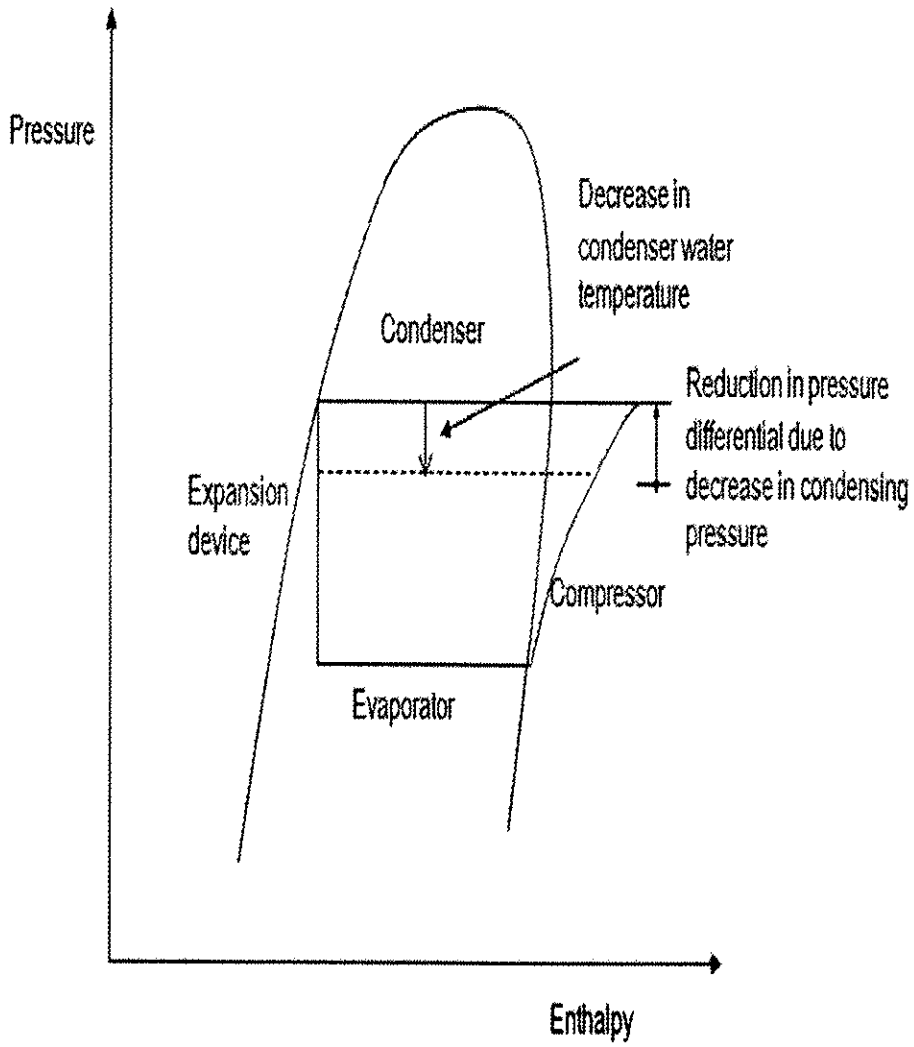




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Condenser water reset

Compressor power reduced by decreasing condensing pressure



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Example – chilled water reset

The efficiency of a particular chiller is 0.6 kW/RT when the chilled water supply temperature is 44°F (≈7°C)

If the chilled water supply temperature is increased to 46°F (≈7.8°C), the chiller efficiency will improve to

0.6 kW/RT x 0.96 = 0.58 kW/RT

(assuming 4% improvement for increasing 2°F)

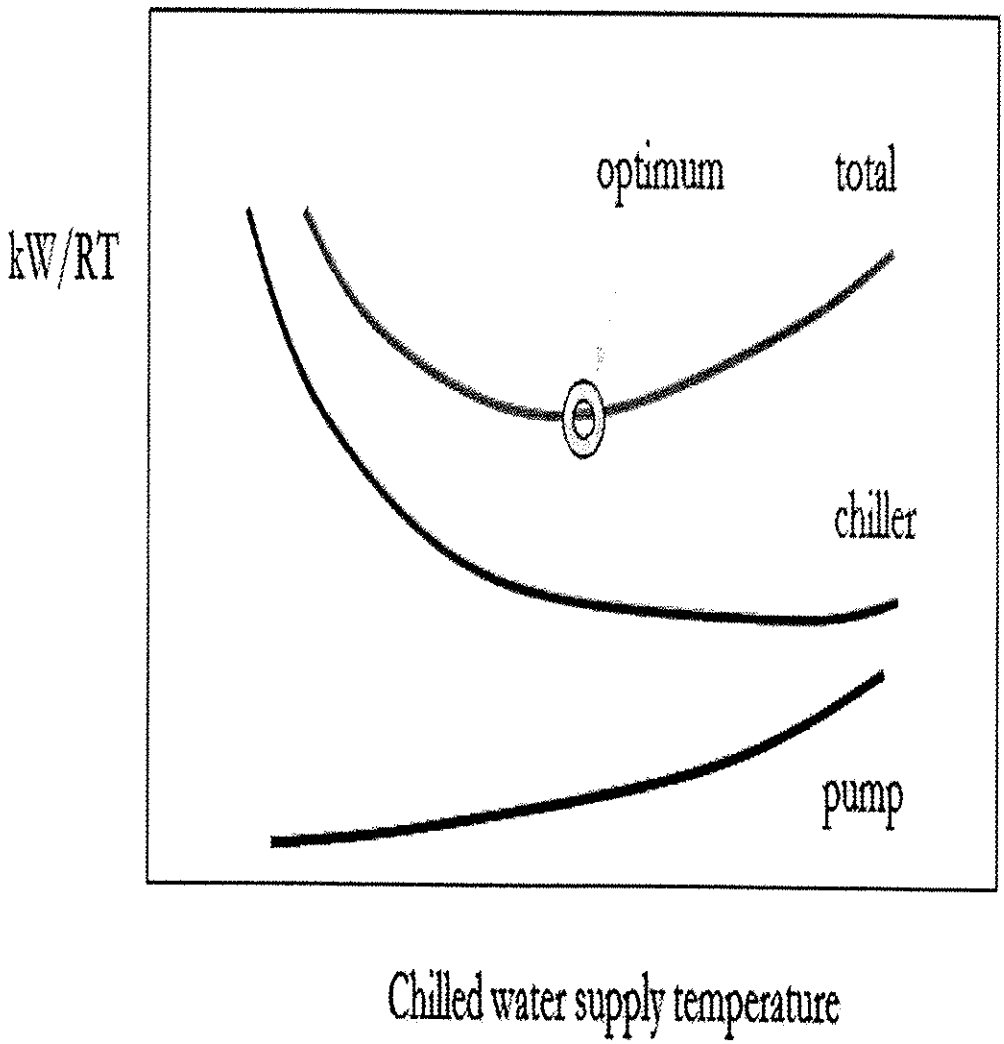
If chiller operates at 500RT, 10 hrs a day,

Saving = (0.6 - 0.58) x 500 x 10 = 100 kWh/day

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Chilled water reset

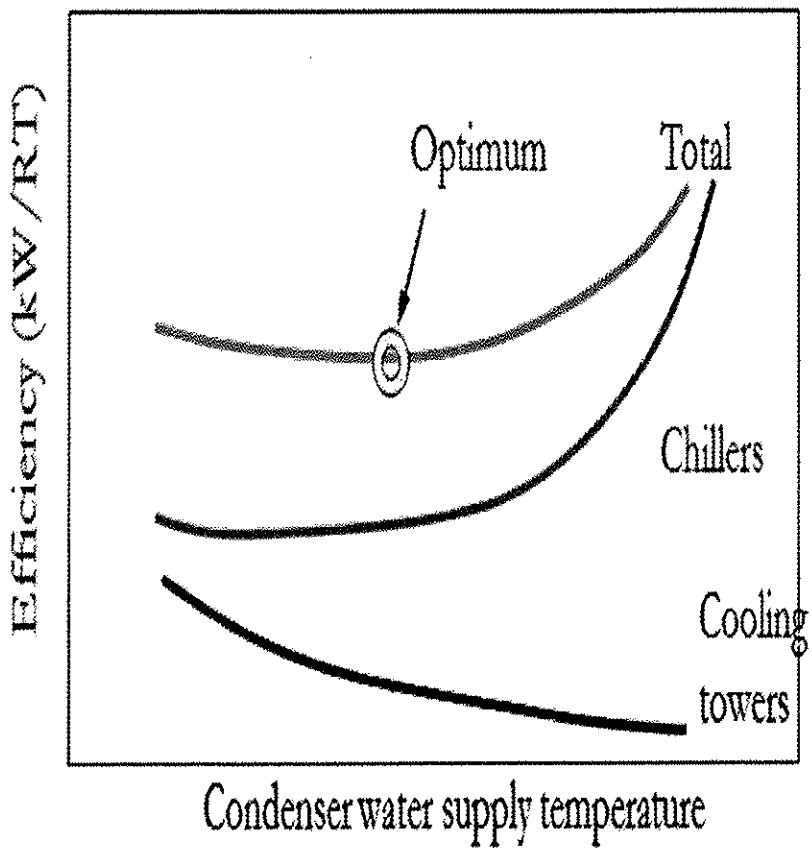
Need to optimise total power



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Condenser water reset

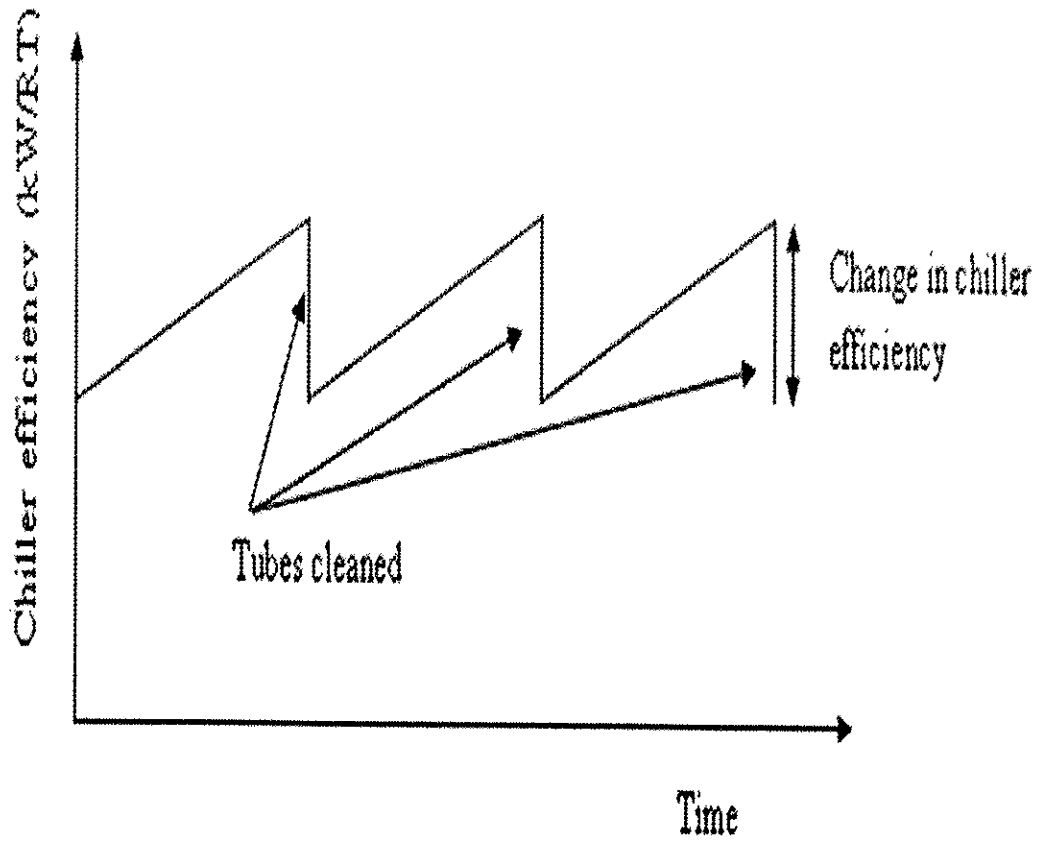
Therefore, need to optimise overall power consumption for chillers & cooling towers



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Maintaining of condenser tubes (contd.)

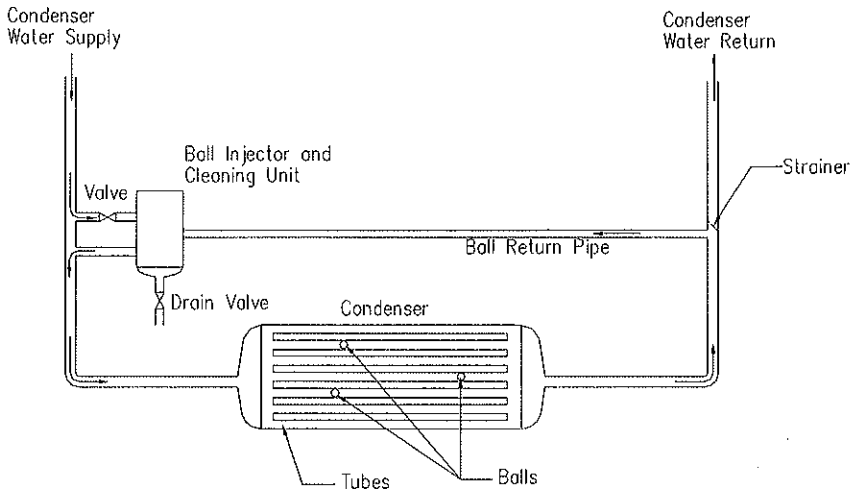
- Water treatment is normally not able to completely eliminate scaling & fouling
- Also blowdown and tube cleaning is periodic
- Results in a "saw-tooth" pattern for chiller efficiency



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Automatic tube cleaning systems

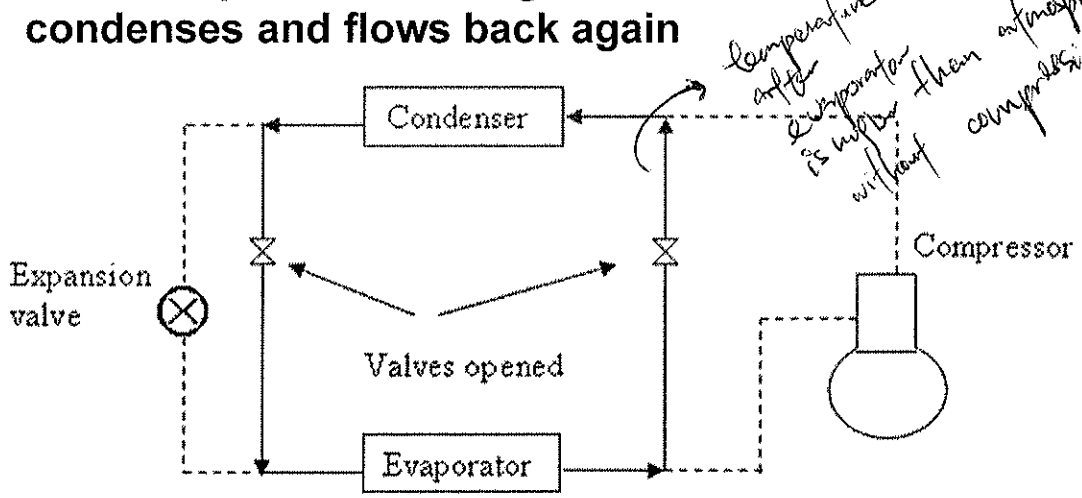
- Ball & brush type
- Need to account for extra pressure losses
- Feasibility depends on condenser approach temperature



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Chiller free cooling

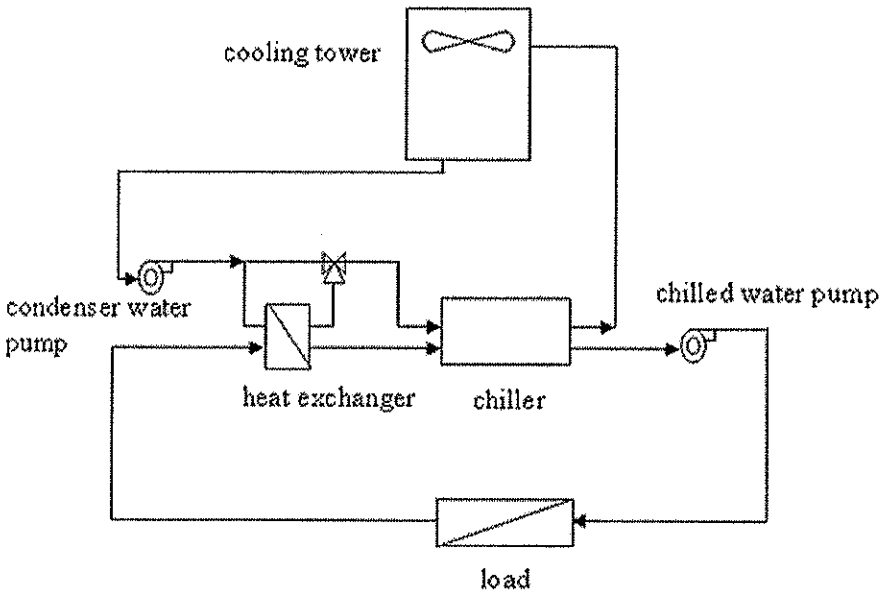
- Involves using chillers to provide cooling with compressor switched off when outdoor wet-bulb temperature is low (winter)
- Chiller acts like a heat pipe where refrigerant evaporates in the evaporator and migrates to the condenser where it condenses and flows back again



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Water side economiser

- Can be used when cooling tower water is cold enough to completely or partially cool chilled water



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Thermal energy storage (TES) systems

A form of storage that stores energy (cold or heat energy) for use at a later time

- Chilled water thermal storage systems use the sensible heat in a body of water
- Ice thermal storage systems use the latent heat of ice
- Eutectic salts (inorganic salts & water) which freeze at temperatures above the freezing point of water

Chilled water or ice produced is used later to produce cooling

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Advantages of TES

A properly designed system can help -

- reduce initial cost by
  - reducing cooling capacity
  - reducing standby equipment
  - reducing need for backup (emergency) equipment
- reduce operating cost by
  - reducing maximum power demand
  - making use of difference in peak & off-peak tariffs
  - improving system efficiency during periods of low cooling demand

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Feasibility of TES

Depends on

- Cooling load profile
  - load for short duration
  - loads occur infrequently / are cyclical
  - loads are not coincident with energy source availability
- Electricity tariffs / availability
  - energy cost is time dependent
  - high demand charges
- Others
  - interruption to cooling cannot be tolerated
  - existing equipment does not have spare peak capacity but has excess off-peak capacity to meet facility expansion

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Thermal storage systems

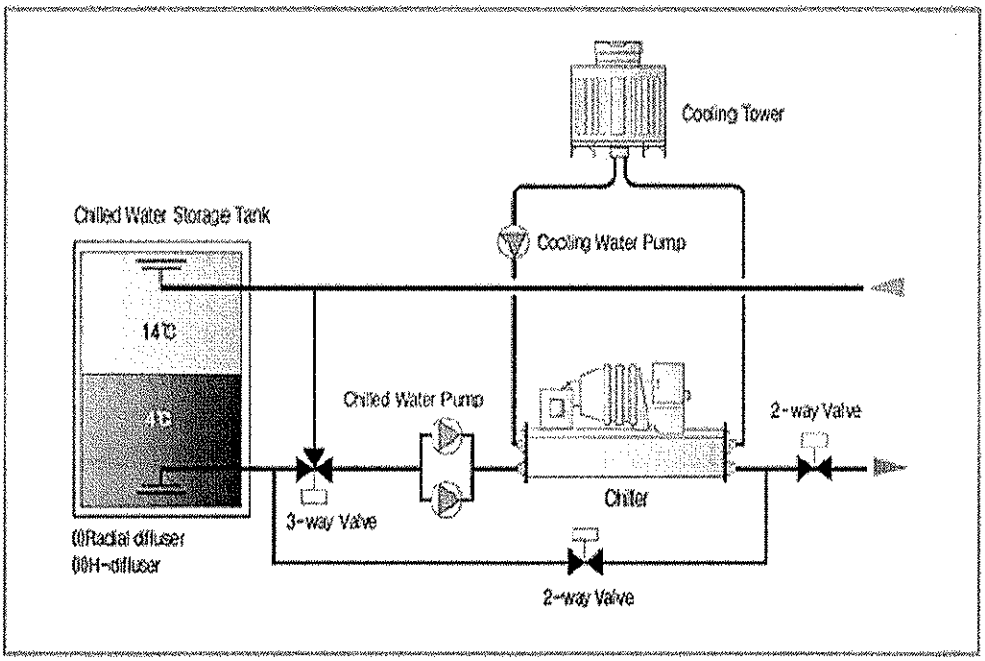
Storage capacity is measured in RT-hours

- **1 RT-hour = 1 RT of cooling for 1 hour**
- **20 RT-hours = 5 RT of cooling for 4 hours**

  or = 10 RT of cooling for 2 hours etc.

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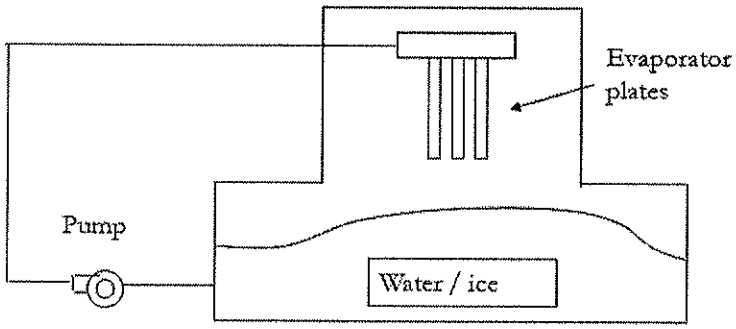
Chilled water storage systems



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Ice harvester

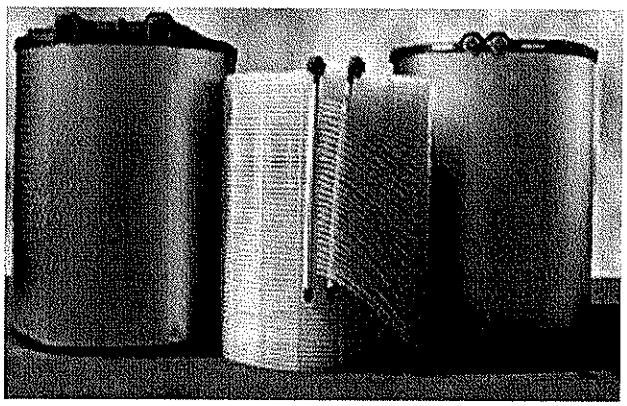
Consists of vertical evaporator plates hung above a storage tank. Water when pumped and distributed over the plates, form ice. Periodically the refrigerant cycle is reversed to warm the plates and "harvest" the ice.



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Ice on-coil systems

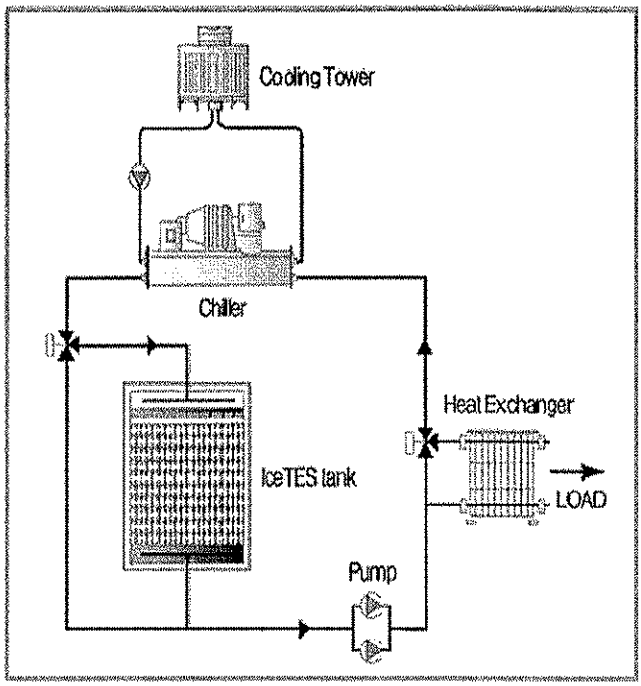
Consists of a heat exchanger coil submerged in a tank. Refrigerant or glycol is passed through the coil to form ice on the outside of it.
To melt the ice and discharge the stored cooling, warm return water is circulated through the tank.



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Encapsulated ice systems

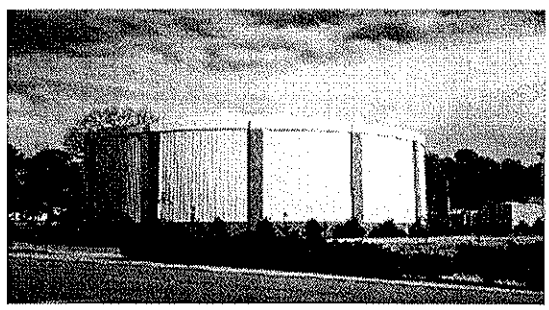
Consists of plastic containers with water which are submerged in storage tanks. Glycol solution from the chillers is circulated through the tank which freezes the water in the containers to form ice. They are later melted to provide cooling.



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Chilled water storage systems

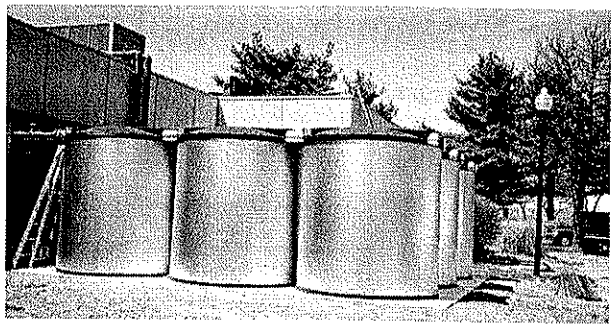
- **Typically water is chilled to 4.5°C to 5.5°C**
- **Can store about 23.2 kJ/kg (10 Btu/lb) at ΔT 10°C**
- **Need about 20 ft^3/RT-hour**
- **Chiller efficiency about 0.6 kW/RT**



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Ice storage systems

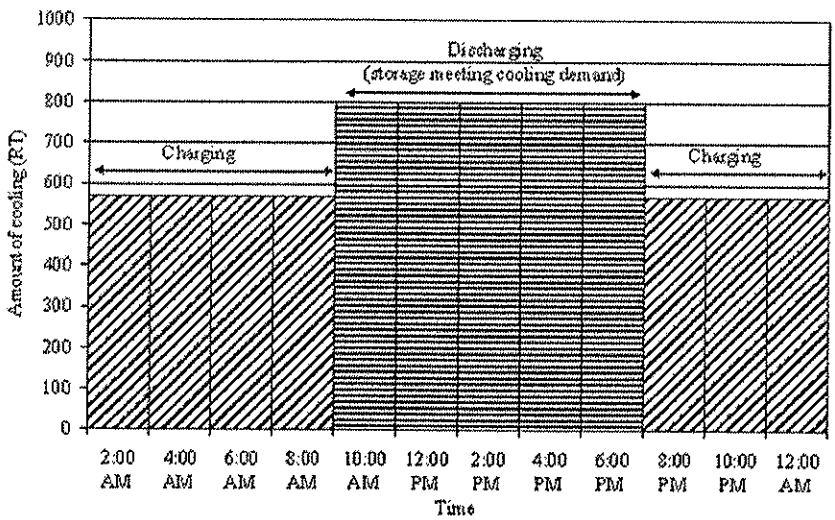
- Operates at about -7°C
- Can store 335 kJ/kg (144 Btu/lb)
- Need about 2 to 3.5 ft^3/RT-hour
- Chiller efficiency about 1 kW/RT (needs much less storage volume but half the efficiency)



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Full storage strategy

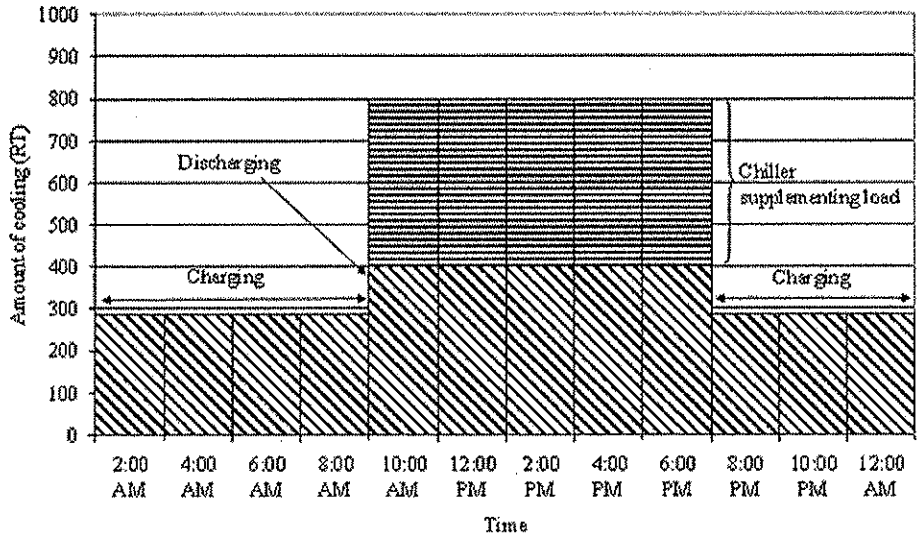
- Entire peak load is shifted to off-peak period
- System operates at full capacity during off-peak period and system discharges during peak period



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Partial storage

- Chillers operate at peak period to meet only part of the load
- System is charged during off-peak period



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Chilled water storage for off-peak cooling

Example

An office building uses a 150RT chiller at night to provide after office hours cooling to satisfy a load of 20RT from 6 pm to 2 am (8 hours)

The resulting chiller efficiency is 1.75 kW/RT

If this after office hours cooling is provided using chilled water storage, the chilled water can be produced using the day chillers operating at 0.65 kW/RT

Daily saving = ([1.75 x off-peak tariff] – [0.65 x peak tariff]) x 20 RT x 8 hours

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Example (contd.)

Storage required

= 20 RT x 8 hours = 160 RT-hours

≈ 24,000 gallons

≈ 90 cubic metres

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MOTORS, PUMPS, FANS AND LIFTS

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LJ Energy Pte Ltd

Course Contents

- Motors
- Fans
- Pumps
- Lifts

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Motor

- Most of the electrical energy consumed in buildings is accounted for by motors which are used for operating equipment such as Chillers, fans, pumps and elevators
- In industrial plant, motors used for pumps, fans, compressors, refrigeration systems and material handling systems also account for a significant portion of the total electricity consumption

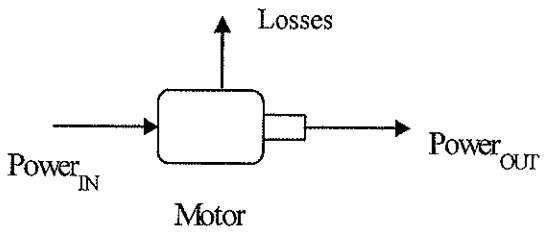
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Motor efficiency

- Efficiency is a measure of how well an electrical device converts the power consumed to useful work
- Although devices such as electrical heaters can convert 100% of the power consumed into heat, devices such as motors cannot convert all the power in to work
- Therefore, it is necessary to provide more than 1Hp to get 1 Hp of mechanical output

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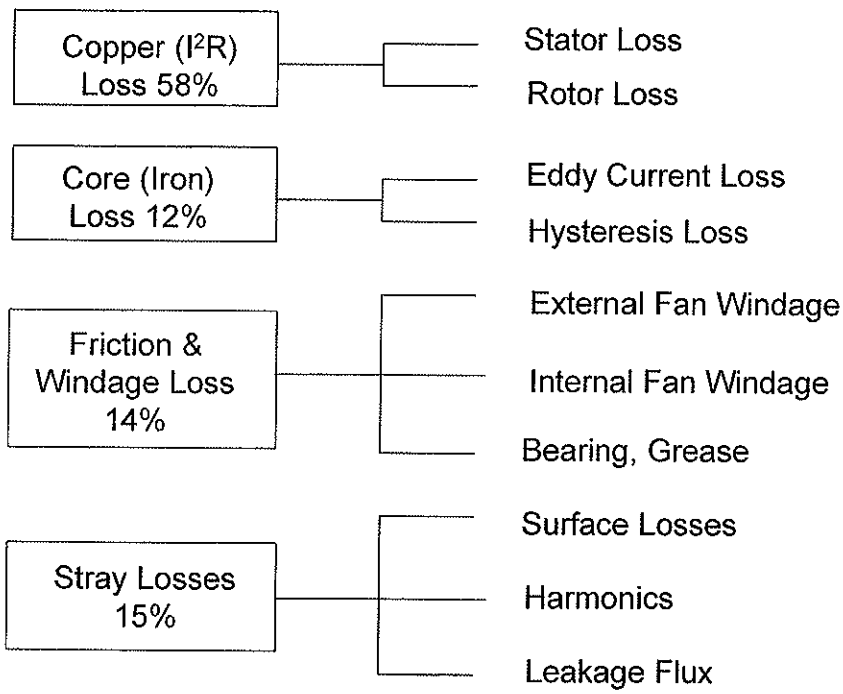
Motor efficiency (contd.)



$$\text{Motor efficiency, } \eta = \frac{\text{Power}_{OUT}}{\text{Power}_{IN}}$$

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Losses in motors



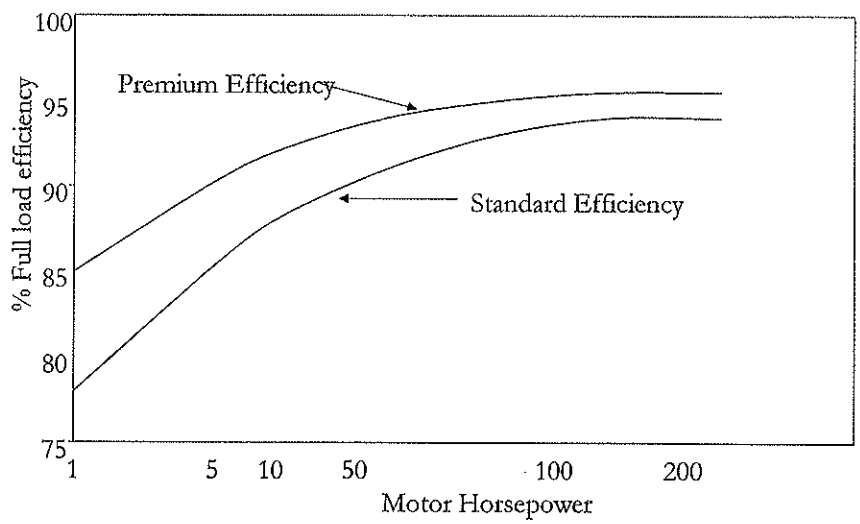
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Motor efficiency (contd.)

- Efficiency of motors depend on capacity and construction
- Efficiency of standard motors range from 78% to 93%
- Premium / High efficiency motors have 3% to 7% better efficiency ratings than standard ones

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Motor efficiency (contd.)



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Motor efficiency standards

- **NEMA**
- **IEC**
- **EU**

Motor type	IEC 60034-30	NEMA, EPACT & EU
Standard	IE 1	Standard, EFF2
High efficiency	IE 2	EPACT, EFF1
Premium efficiency	IE 3	NEMA Premium

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Economics of energy efficient motors

Replacing existing motors depend on:

- **Efficiency of existing motor**
- **Motor operating hours**
- **Age of motor**
- **Motor loading**
- **Electricity tariff**
- **Cost of new high efficiency motor**
- **Incentives**

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Feasibility of replacing motors

Example

Consider an 18.7 kW (25 Hp) motor of 88% efficiency (standard efficiency) operating 12 hours a day and 365 days a year. Calculate the savings that will result if it is replaced with a 93% efficiency (premium efficiency) motor (assume motor is loaded to full capacity).

Estimate the simple payback period if the cost of the new motor is $3,000 and the average electricity tariff is $0.15/kWh.

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Feasibility of replacing motors

$$\text{Energy saved in kWh} = \text{Motor kW x Operating hours x} \left[\frac{1}{\eta_S} - \frac{1}{\eta_P} \right]$$

Annual electrical saving

$$= 18.7 \times 12 \times 365 \left[\frac{1}{0.88} - \frac{1}{0.93} \right] \text{ kWh/year}$$

= 5,004 kWh/year

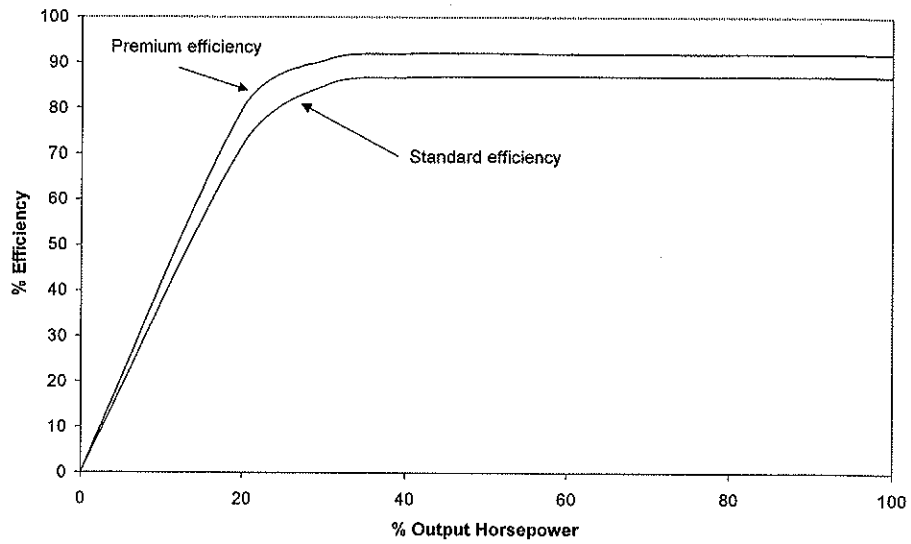
Cost savings = 5,004 x 0.15
= $750.60 / year

Simple payback period = 3000 / 750.60
= 4 years

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Motor loading and efficiency

- Operating efficiency of motors also depend on their loading
- Generally, efficiency drops when loading is < 40%



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Estimation of motor loading

$$\text{Motor loading} = \frac{\text{input power (kW) x efficiency}}{\text{motor rated power (kW)}}$$

(motor input power x motor efficiency = motor output power)

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Replacing oversized motors

Example

The rated efficiency of a standard 55 kW motor used for a water pump is 90%. When the pump is operating at its full load conditions, the power drawn by the motor is measured to be only 9 kW. Estimate the actual motor operating efficiency.

If the pump operates 24 hours a day, estimate the amount of electrical energy that can be saved if the pump motor is replaced with a smaller capacity motor.

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Example (contd.)

The estimated loading of the motor is 9x0.9 / 55 = 15%
From the earlier figure, the motor operating efficiency is expected to be about 55% at this load

Based on this motor efficiency,
Motor output power = 0.55 x 9 = 5 kW

If a 5.5 kW motor is used for this application, the expected motor efficiency is about 85%

The input power for the new motor = 5 / 0.85 = 5.9 kW

Electrical energy saved = (9 – 5.9) x 24 = 74.4 kWh/day

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Fans

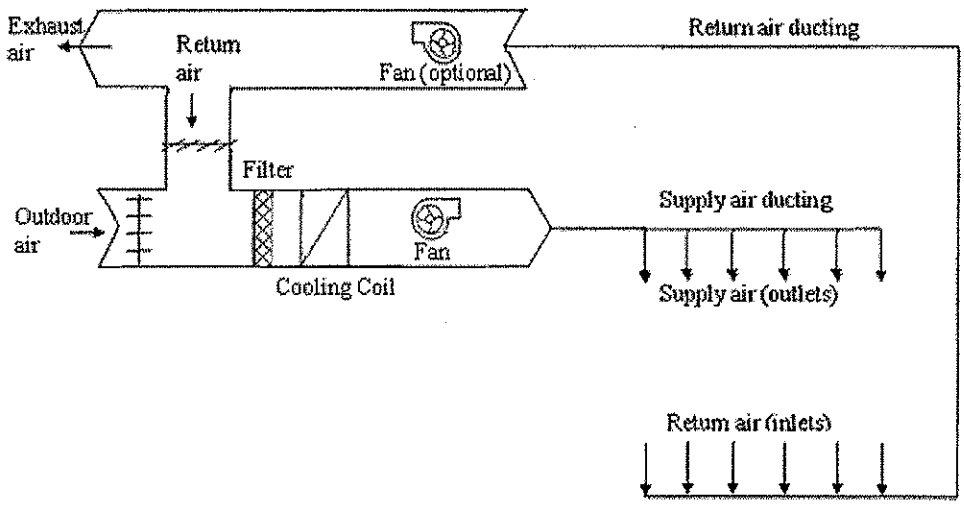
Fans are used for

- Cooling & heating
- Ventilation
- Smoke exhaust / removal of contaminants

- Fans provide the necessary energy to move air by overcoming frictional losses in the ducting and pressure losses due to components in the system such as fittings, filters, coils and various equipment

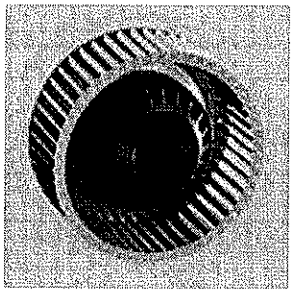
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Typical system in buildings

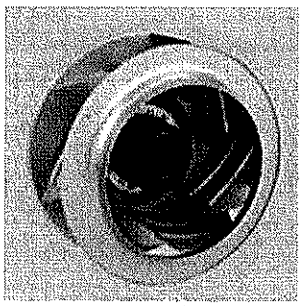


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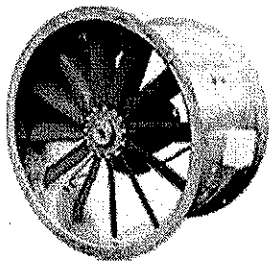
Common types of fans



Forward curved fan



Backward curved fan



Axial flow fan

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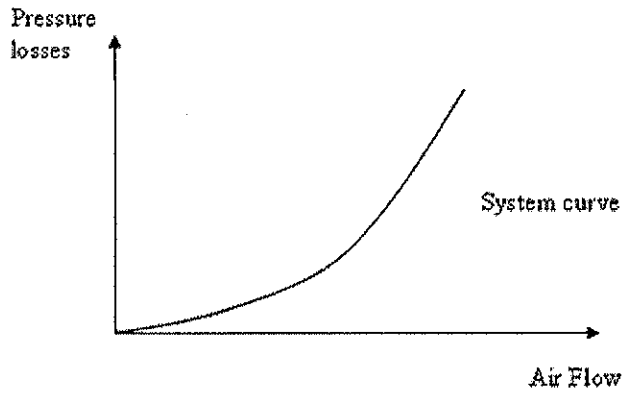
Comparison of fans

Fan type	Air flow	Pressure	Efficiency
Axial flow	High	Low	60 – 80%
Centrifugal – forward curves	High	Low	50 – 70%
Centrifugal – backward curved	Low	High	65 – 85%

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System characteristics

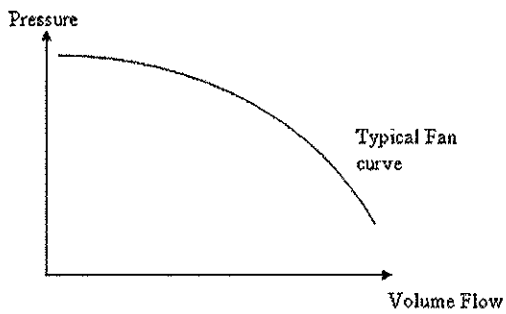
- Fans are rated based on flow rate and pressure head
- Pressure developed by fans is used to overcome resistances in a system
- Pressure losses are proportional to square of air flow rate ($\Delta P \propto Flow^2$)

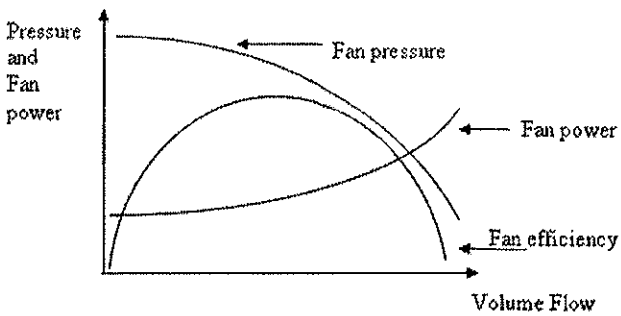


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Fan characteristic curves

Relationship between air flow, pressure, efficiency, motor power etc. at different speeds and impeller sizes

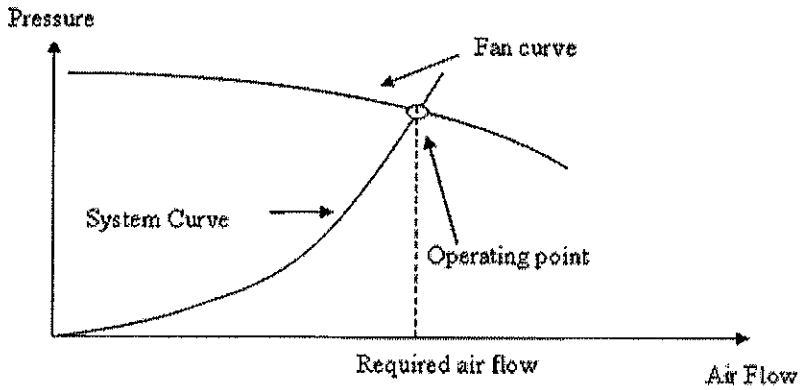




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Fan selection

- **Fans are selected so that fan curve intersects the system curve at the desired operating point**



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Fan power

$$\text{Fan impeller power} \propto \frac{\text{Air flow rate x Pressure developed}}{\text{Efficiency}}$$

$$\text{Fan impeller power (kW)} = \frac{\text{Flow rate } (m^3/s) \text{ x Pressure developed } (N/m^2 \text{ or Pa})}{1000 \text{ x Efficiency}}$$

$$\text{Fan brake horsepower} = \frac{\text{Flow rate (cfm) x Pressure difference (in. water)}}{6350 \text{ x Efficiency}}$$

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Affinity laws

	Change in speed (N)	Change in impeller diameter (D)
Flow (Q)	$Q_2 = Q_1\left(\frac{N_2}{N_1}\right)$	$Q_2 = Q_1\left(\frac{D_2}{D_1}\right)^3$
Pressure (Δp)	$\Delta p_2 = \Delta p_1\left(\frac{N_2}{N_1}\right)^2$	$\Delta p_2 = \Delta p_1\left(\frac{D_2}{D_1}\right)^2$
Power (P)	$P_2 = P_1\left(\frac{N_2}{N_1}\right)^3$	$P_2 = P_1\left(\frac{D_2}{D_1}\right)^5$

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Ducting system design

- **Fan energy consumption depends on air flow rate and pressure losses**
- **Air flow required depend on load requirements, while pressure losses depend on friction and dynamic losses**
- **Friction losses**
  - **resistance to fluid flow by duct**

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Ducting system design (contd.)

- Dynamic losses are due to
  - change in flow direction (elbows, tees, bends)
  - change in velocity (diverging & converging sections)
  - fittings (dampers)
  - fan discharge and intake losses

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Friction losses in ducts

$$\Delta P_f = \frac{f.L.v^2}{2.g.D_m}$$

- Friction losses can be reduced by
  - increasing duct area (lower velocity)
  - reducing duct length
  - using material with lower friction factor

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Dynamic losses in fittings

$$\Delta P_d = C_o . P_v$$

C_o = loss coefficient

P_v = Velocity pressure = ½ ρ v^2

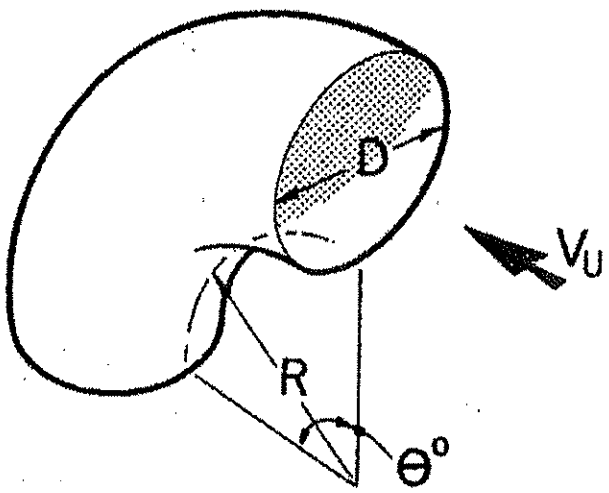
where, ρ = density of air

- Dynamic losses can be reduced by
  - minimising number of fittings
  - long radius bends
  - gradual transformation in duct cross-section

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Dynamic loss data

FITTING No. 011 CIRCULAR RADIUSED BEND



RADIUS RATIO R/D	k_T
0.25	0.45
0.50	0.34
1.0	0.24
1.5	0.23
2.5	0.22

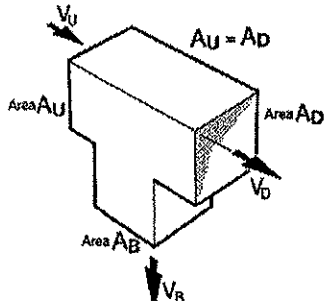
Bend Angle correction as for Fitting No. 001

IHVE

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Dynamic loss data

FITTING No. 401 RECTANGULAR 90° TAKE-OFF OR FITTING No. 411 CIRCULAR 90° TAKE-OFF



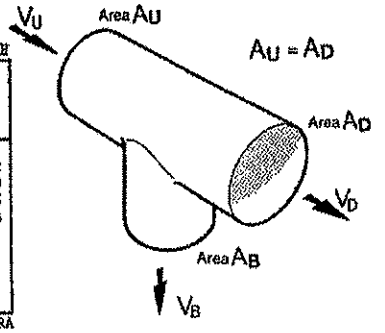
BRANCH PATH

VELOCITY RATIO V_B/V_U	AREA RATIO A_B/A_D 0.2	0.3	0.5	0.7	1.0
0.4	9.69	8.75	6.88	5.94	5.31
0.6	4.58	4.31	3.33	2.84	2.5
0.8	3.13	2.81	2.03	1.72	1.72
1.0	2.40	2.00	1.40	1.25	1.25
1.2	1.88	1.74	1.11	0.97	–
1.5	1.56	1.56	0.84	–	–
2.0	1.50	1.50	0.88	–	–
2.5	1.28	1.44	–	–	–

STRAIGHT THROUGH

VELOCITY RATIO V_D/V_U	k_T
0.4	0.12
0.5	0.09
0.6	0.06
0.7	0.03
0.8–1.0	0

HVRA



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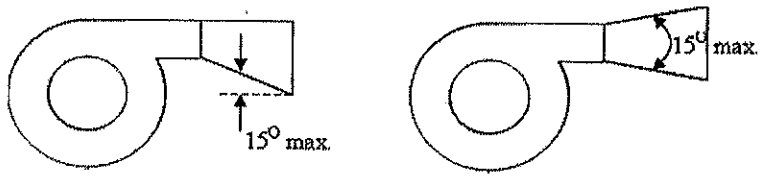
Fan discharge & intake losses

- Fans impart dynamic pressure on the air due to centrifugal action
- This dynamic pressure has to be converted to static pressure to enable the fan to overcome the system losses
- Usually, a minimum duct length is required after the fan to enable this static regain to be completed
- Therefore, a system design should attempt to use straight ductwork for 3 to 5 equivalent duct diameters downstream of the fan discharge

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Fan discharge & intake losses (contd.)

- Where transition to a duct with larger area is required after the fan, a taper having an included angle of no more than 15° should be used



- Where fans discharge into a plenum, losses occur due to the sudden enlargement in flow area
- The addition of a short discharge duct of only one or two equivalent diameters in length significantly reduces this sudden enlargement loss

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Fan discharge & intake losses (contd.)

- Duct bends, immediately at the fan discharge also create a high static pressure drop due to turbulence and the velocity profile existing at the discharge
- When an elbow must be used at the fan discharge, it is recommended not to have a short-radius elbow
- Preferably, an elbow with a minimum radius of 1.5 times the equivalent duct diameter should be used

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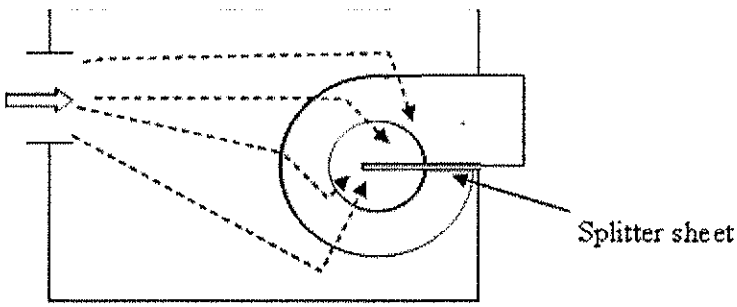
Fan discharge & intake losses (contd.)

- Non-uniform flow into the suction of a fan is typically caused by an elbow installed too close to the fan inlet
- This results in turbulent and uneven flow distribution at the fan impeller leading to lower fan efficiency and higher fan power
- If it is necessary to have a sharp bend at the fan inlet, vanes and a splitter can be installed to minimize losses

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Fan discharge & intake losses (contd.)

- If the opening is not vertically centered to the fan inlet, adding a simple splitter sheet on each side of the fan helps to improve the performance of the fan



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Coil face velocity

- Pressure loss across cooling / heating coils depend on velocity of air flowing through them (face velocity)
- The pressure drop across a coil is proportional to the square of the velocity
- Reduction in coil face velocity can be achieved by making the coil bigger (higher first cost)
- Ideally, coils should be selected based on life cycle cost

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Example - Low face velocity coil

For a system delivering 10 m^3/s, the pressure drop across a cooling coil is 200 Pa and the face velocity is 2.5 m/s.

Calculate the pressure drop and the reduction in fan power if the face velocity is reduced to 1.0 m/s for this application.

Assume the fan efficiency is 70%.

$Q = 10\ m^3/s$

$v_1 = 2.5\ m/s$

$v_2 = 1.0\ m/s$

Δp_1 (coil) = 200 Pa

Δp_2 (coil) $= \Delta p_1$ (coil) x $(v_2 / v_1)^2 = 200 \times (1.0 / 2.5)^2 = 32$ Pa

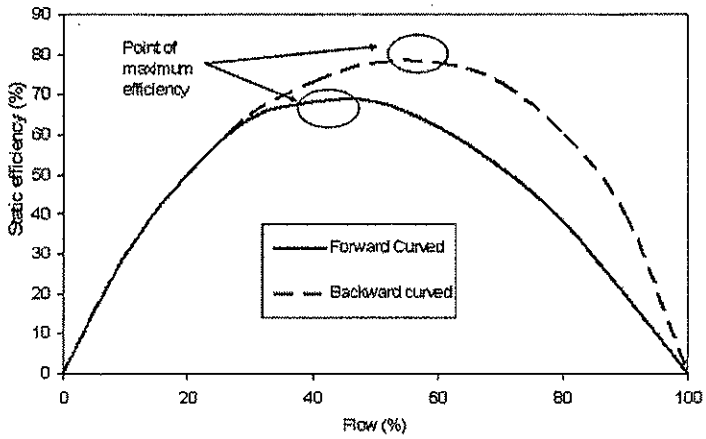
Reduction in pressure drop across the coil = (200 – 32) = 168 Pa

Reduction in fan power = [10 (m^3/s) x 168 (Pa)] / [1000 x 0.7] = 2.4 kW

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Fan efficiency

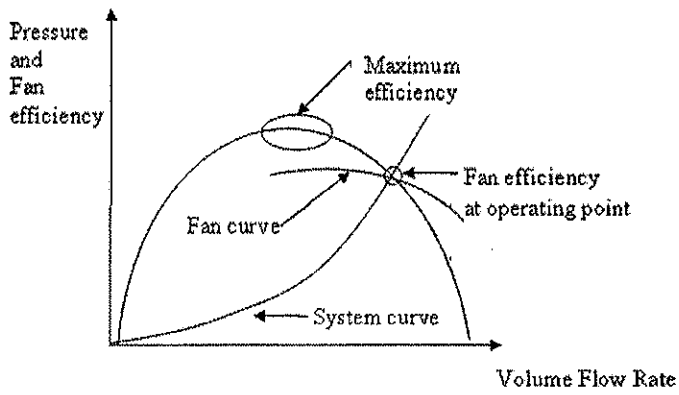
- Backward curved fans have a higher efficiency than forward curved fans (but higher first cost)



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Fan efficiency (contd.)

- Fan efficiency also depends on operating point

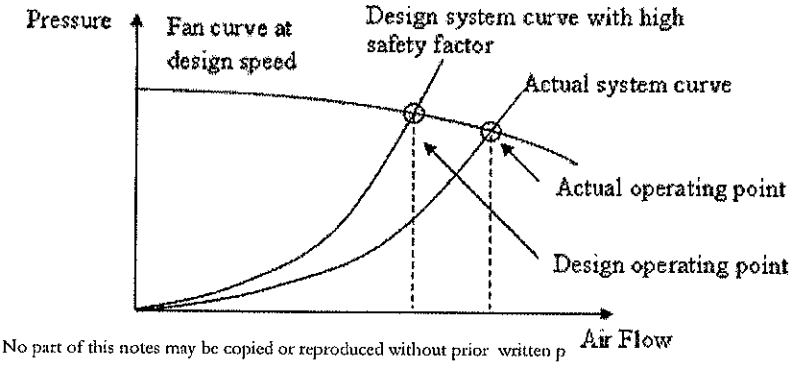


- Therefore, need to select fan which has a high efficiency at the desired operating point

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Air flow rate

- Fans are selected based on design air flow rate required to meet load requirements and expected pressure losses
- Safety factors are used to account for inaccuracy in the estimation of pressure losses and change in duct layout during installation
- If safety factor used is too high, resultant air flow rate will be higher than needed



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Air flow rate

- Since air flow results in extra fan power, air flow should be reduced to required value
- Ideally, should measure air flow and compare with design values
- Air flow rate can be reduced by reducing fan speed (changing pulleys or using VSDs)

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CAV vs VAV

Constant air volume (CAV) systems

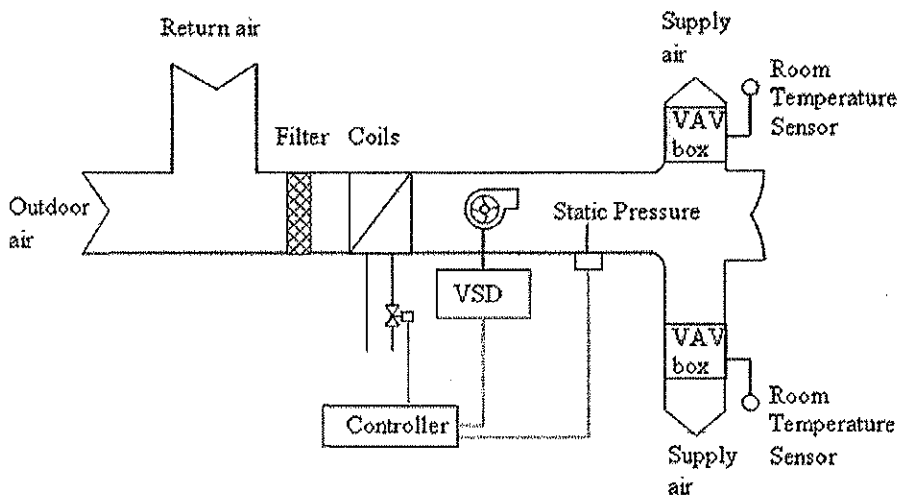
- Constant air flow rate
- Supply air temperature is varied in response to load changes
- Constant fan speed and constant fan power
- Less dehumidification at part-load

Variable air volume (VAV) systems

- Constant supply air temperature
- Air flow rate is varied in response to load changes
  - dampers
  - IGVs
  - VSDs
- Fan energy savings at part-load

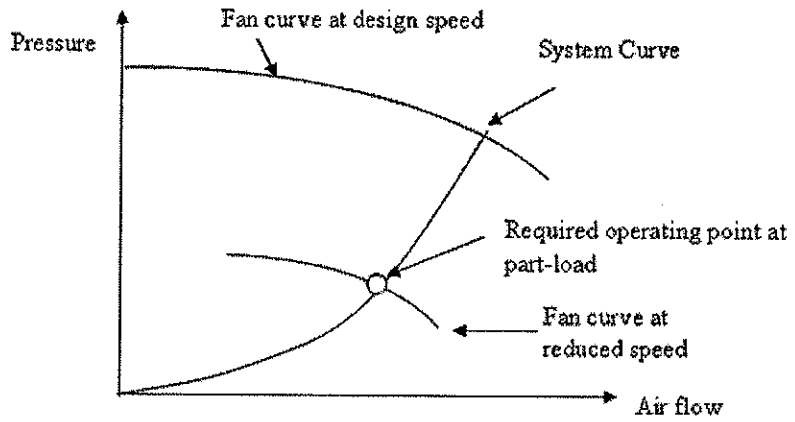
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Use of VSDs



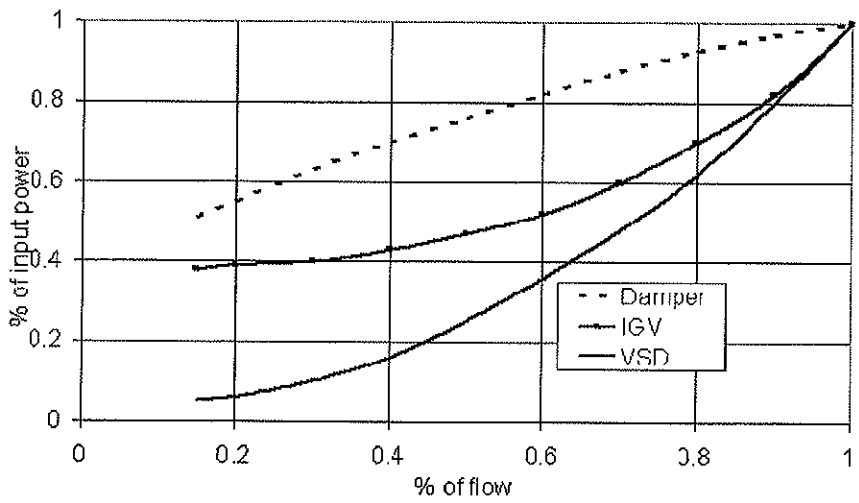
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Use of VSDs (contd.)



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Comparison of control strategies



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Cooling tower fans

Energy saving opportunities

- Capacity control
- Free cooling
- High efficiency fans

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Cooling Tower Capacity Control

- In most cases, operation of cooling towers is interlocked with the system it serves (eg. chillers)
- Often system load varies during operation, but cooling tower capacity is maintained at a fixed value
- It is possible to vary cooling tower capacity in relation to changes in load
- Cooling tower capacity can be modulated by varying the air flow rate
  - Fan staging
  - Variable speed fans

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Cooling Tower Capacity Control (contd.)

Fan staging

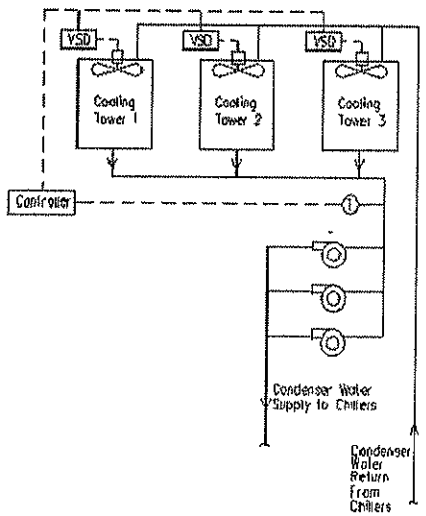
- Involves switching on / off cooling tower fans in response to changes in heat rejection load

Variable speed fans

- Involves varying the speed of cooling tower fans to modulate cooling tower capacity to match load requirements
- Fan speed can be varied to maintain a set water supply temperature or to maintain a set "approach temperature"

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Cooling Tower Capacity Control (contd.)



Since power consumption is proportional to the cube of the fan speed, theoretically, 20% reduction in load can lead to 50% reduction in fan power ($0.8^3 = 0.51$)

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Variable speed fans (contd.)

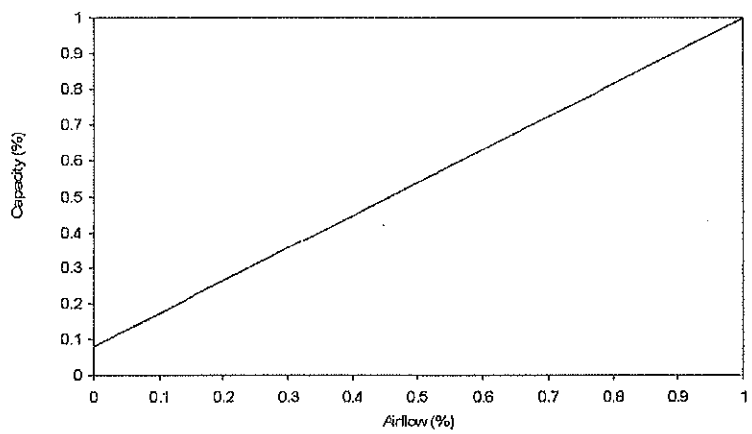
Fan power can also be reduced by operating extra cooling towers because with higher heat transfer area, less air flow is required to provide the same heat rejection capacity

- If two towers are operated to provide the heat rejection equivalent to the capacity of one tower, the two cooling towers need to operate at 50% speed
- Power consumption of each tower will be 12.5% (0.5^3=0.125)
- Saving in power consumption will be 75% [1- (0.125 x 2)=0.75]

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Free cooling

- Cooling tower capacity is proportional to air flow
- Typically, cooling towers can provide about 5% of the cooling capacity with the fans switched off



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Free cooling (contd.)

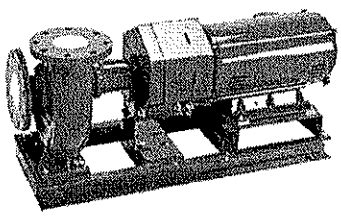
- Therefore, in some installations with a large number of cooling towers, it may be possible to achieve the required heat rejection at low load conditions by just circulating the water through the towers
- For instance, an installation with 5 units of 500 RT capacity can provide 125 RT of "free cooling" capacity (5 x 500 x 5% = 125)

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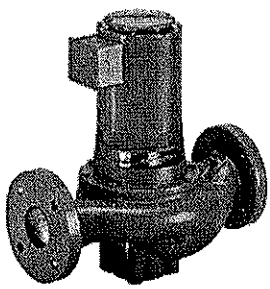
Pumping systems

- Various pumping systems are used in buildings
  - chilled water, condenser water, cold water and hot water

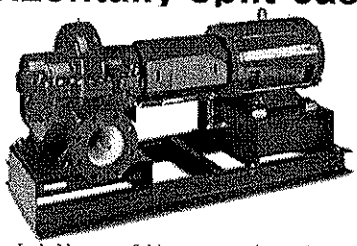
- End-suction



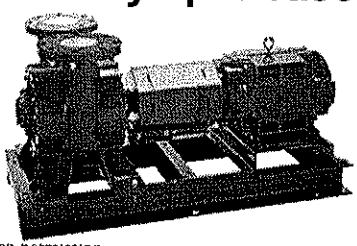
In-line



- Horizontally split-case



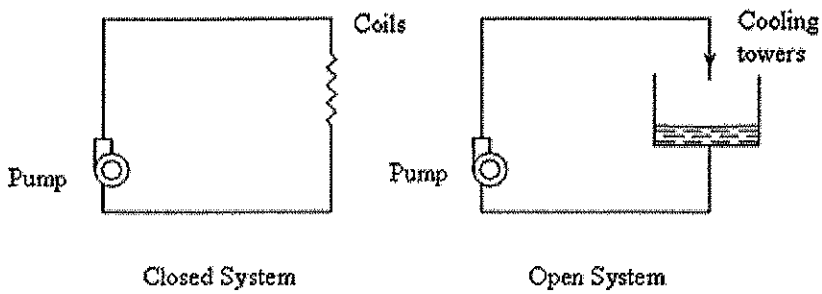
Vertically split-case



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Types of pumping systems

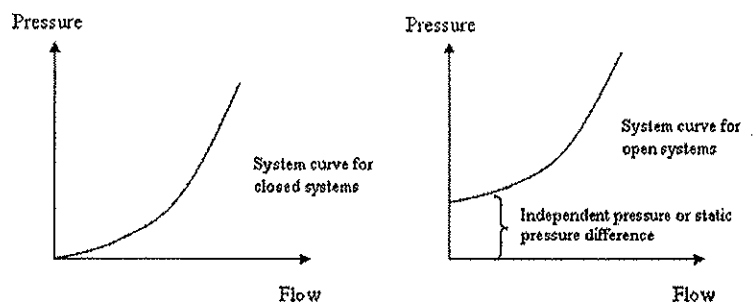
- Open and closed systems



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System characteristics

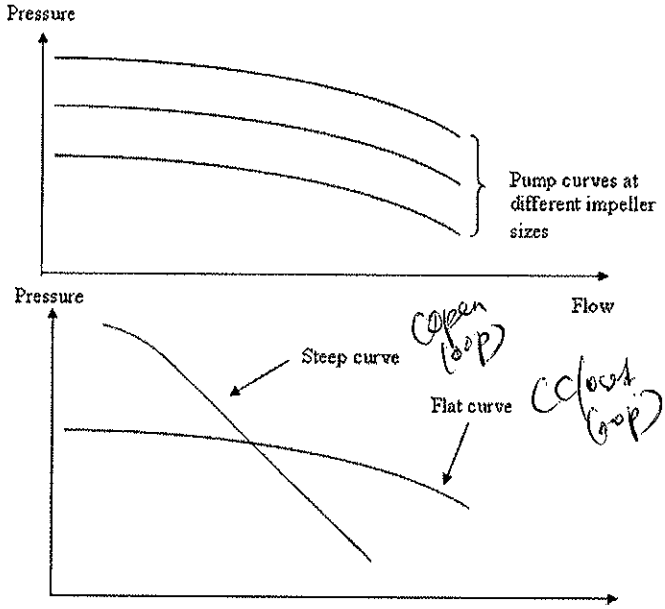
- Pumps are rated based on flow rate and pressure head
- Pressure developed by pumps is used to overcome resistances in the system and head difference in open systems
- Pressure losses are proportional to square of flow rate ($\Delta P \propto Flow^2$)



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Pump characteristic curves

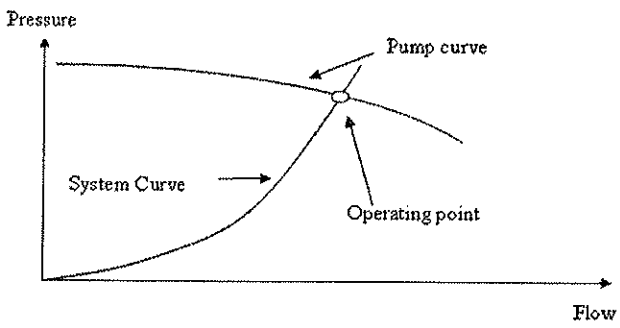
- Performance data for flow, pressure head, efficiency, motor power etc. at different speeds and impeller sizes



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Pump selection

- Pumps are selected so that pump curve intersects the system curve at the desired operating point



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Pump power

$$\text{Pump power} \propto \frac{\text{Liquid flow rate x Pressure difference}}{\text{Efficiency}}$$

$$\text{Pump impeller power (kW)} = \frac{\text{Flow rate } (m^3/s) \text{ x Pressure difference } (N/m^2)}{1000 \text{ x Efficiency}}$$

$$\text{Pump brake horsepower} = \frac{\text{Flow rate (Usgpm) x Pressure difference (ft. water)}}{3960 \text{ x Efficiency}}$$

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Affinity laws

	Change in speed (N)	Change in impeller diameter (D)
Flow (Q)	$Q_2 = Q_1\left(\frac{N_2}{N_1}\right)$	$Q_2 = Q_1\left(\frac{D_2}{D_1}\right)$
Pressure (Δp)	$\Delta p_2 = \Delta p_1\left(\frac{N_2}{N_1}\right)^2$	$\Delta p_2 = \Delta p_1\left(\frac{D_2}{D_1}\right)^2$
Power (P)	$P_2 = P_1\left(\frac{N_2}{N_1}\right)^3$	$P_2 = P_1\left(\frac{D_2}{D_1}\right)^3$

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Losses in piping systems

Friction losses depending on

- pipe size (flow velocity)
- pipe length
- pipe material

Dynamic losses

- changes in flow area (velocity)
- changes in flow direction
- obstructions

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Dynamic losses in fittings

$$\Delta P = K \rho \frac{V^2}{2}$$

ΔP = pressure loss in Pa

K = loss coefficient

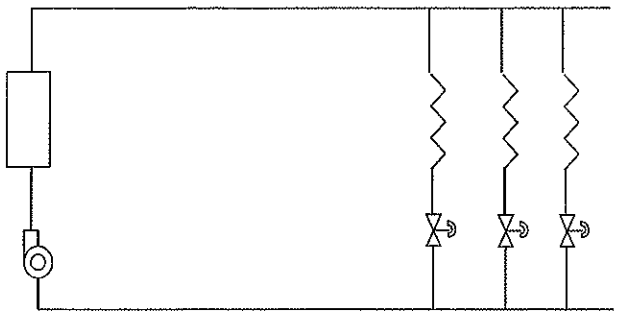
V = Velocity (m/s)

ρ = density (kg/m^3)

Nominal Pipe Dia., mm	90° Ell Reg.	90° Ell Long	45° Ell Long	Return Bend Standard	Return Bend Long-Radius	Tee-Line	Tee-Branch	Glove Valve	Gate Valve	Angle Valve	Swing Check Valve
25	0.43	0.41	0.22	0.43	0.43	0.26	1.0	13	—	4.8	2.0
32	0.41	0.37	0.22	0.41	0.38	0.25	0.95	12	—	3.7	2.0
40	0.40	0.35	0.21	0.40	0.35	0.23	0.90	10	—	3.0	2.0
50	0.38	0.30	0.20	0.38	0.30	0.20	0.84	9	0.34	2.5	2.0
65	0.35	0.28	0.19	0.35	0.27	0.18	0.79	8	0.27	2.3	2.0
80	0.34	0.25	0.18	0.34	0.25	0.17	0.76	7	0.22	2.2	2.0
100	0.31	0.22	0.18	0.31	0.22	0.15	0.70	6.5	0.16	2.1	2.0
150	0.29	0.18	0.17	0.29	0.18	0.12	0.62	6	0.10	2.1	2.0
200	0.27	0.16	0.17	0.27	0.15	0.10	0.58	5.7	0.08	2.1	2.0
250	0.25	0.14	0.16	0.25	0.14	0.09	0.53	5.7	0.06	2.1	2.0
300	0.24	0.13	0.16	0.24	0.13	0.08	0.50	5.7	0.05	2.1	2.0

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Pump over-sizing

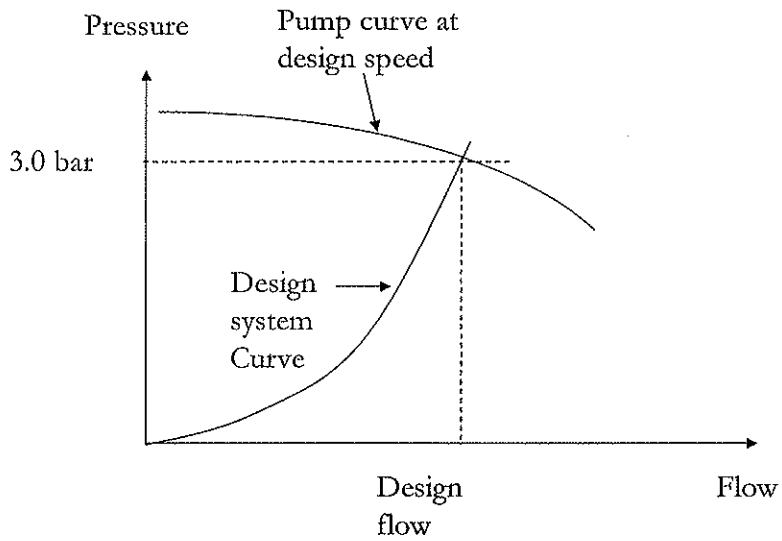


Example

Head loss	**bar**
Evaporator	0.5
Piping (friction losses)	1.0
Valves & fittings	0.4
Cooling coils	0.5
Total	2.4
Total with 25% safety factor	**3.0**

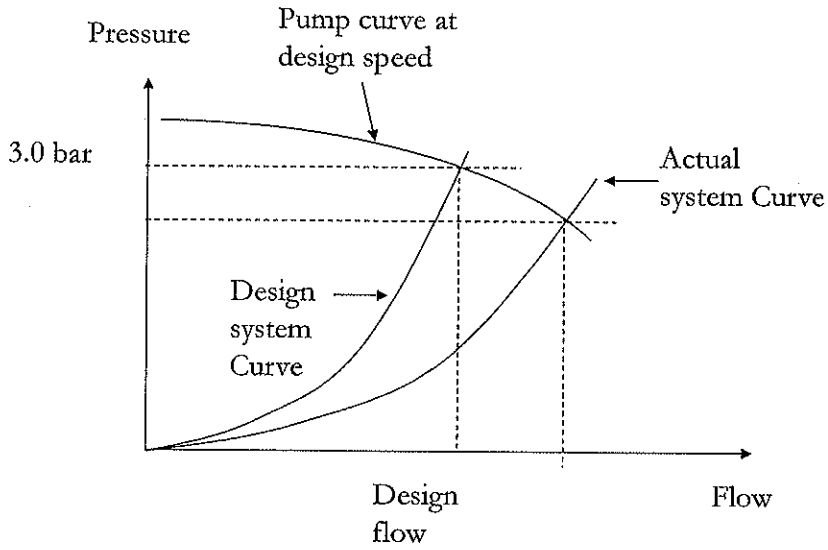
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Pump selection



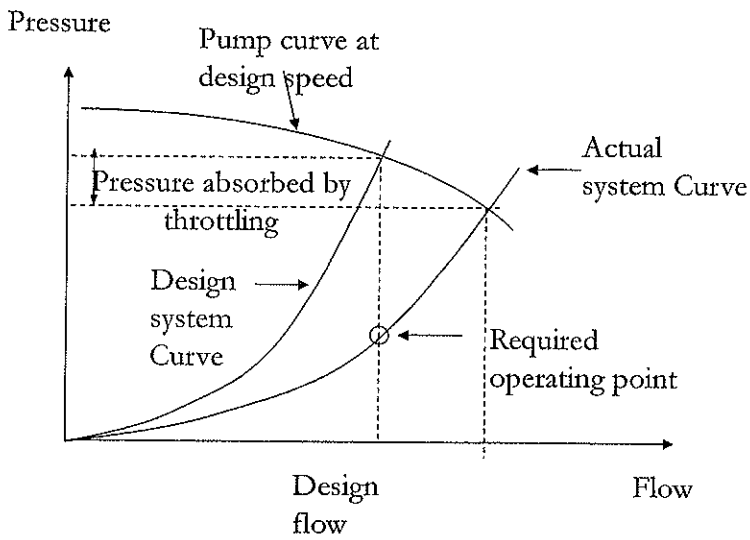
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Actual pump operation



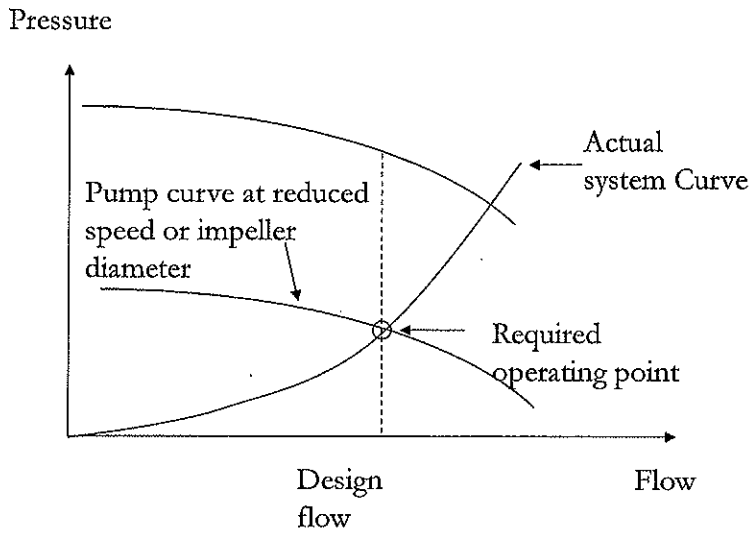
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Throttling of pumps



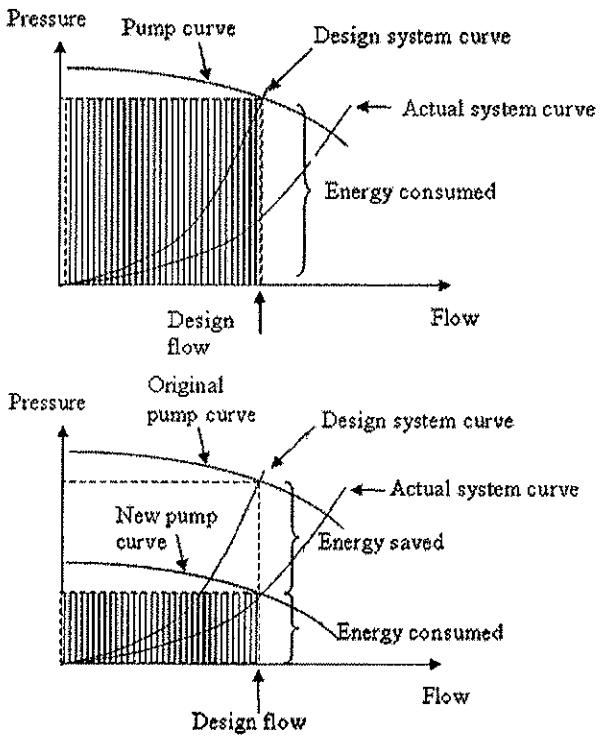
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Required operating point



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Energy savings



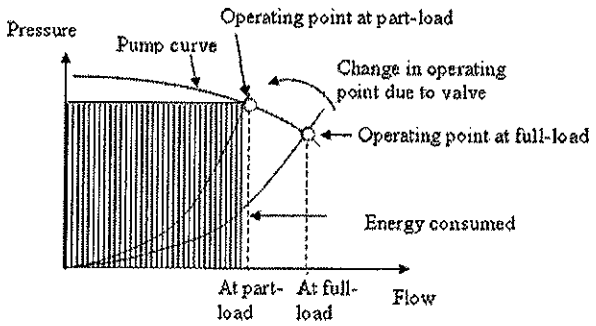
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Constant flow vs variable flow

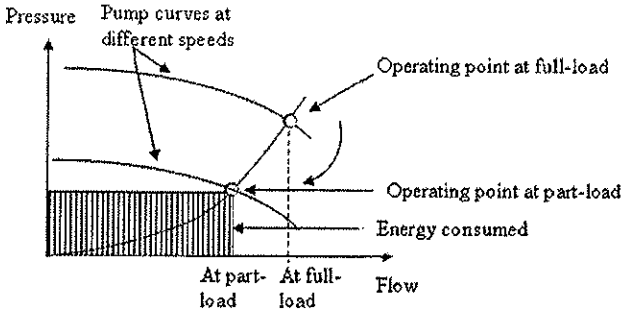
- Loads are normally is not constant
- Therefore, can vary water flow to match load requirements
- In constant flow systems, system curve moves along pump curve and energy consumption remains almost constant
- If flow rate can be varied with load by modulating pump speed, pumping energy consumption can be reduced

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Relative energy consumption



Constant flow



Variable flow

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Pressure drop in equipment

- When water flows through various equipment, pressure losses result due to flow resistance
- The pumps need to overcome this resistance
- Higher the resistance, higher the pump power consumption (pump kW $\propto$ Q x ΔP)
- Therefore when purchasing equipment, the pressure drop across them should be considered to minimise pumping power

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Example - Pressure drop

Example

Consider the following two chiller options

	Option A	Option B
Chiller capacity	500 RT	500 RT
Pressure drop across evaporator	90 kN/m^2 (30 ft water)	30 kN/m^2 (10 ft water)
Chilled water flow rate	75.6 l/s (1200 Usgpm)	75.6 l/s (1200 Usgpm)

Theoretical pump power consumption to overcome the resistance across the evaporator can be calculated as follows (assuming efficiency of 100%):

Pump kW = [Flow in m^3/s x Pressure difference in N/m^2] / 1000
Option A, pump kW = [0.0756 x 90,000] / 1000 = 6.8 kW
Option B, pump kW = [0.0756 x 30,000] / 1000 = 2.3 kW

Pump kW savings due to Option B = (6.8 – 2.3) = 4.5 kW

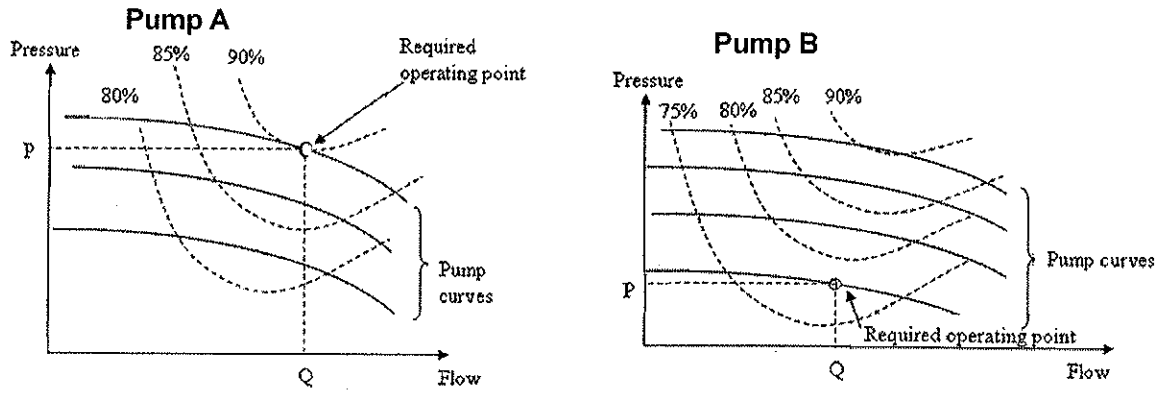
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Pump efficiency

- **Pumping power consumption also depends on pump efficiency**

$$\text{Pump brake horsepower} = \frac{\text{Flow rate } (m^3/s) \times \text{Pressure difference } (N/m^2)}{1000 \times \text{Efficiency}}$$

- **At the same operating conditions (Flow, Q & Head, P), two different pumps may have two different operating efficiencies**



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Example - Pump efficiency

Example

A system requires a pump with a capacity of 80 l/s and a head of 150 kN/m^2. Calculate the savings in pump power that can be achieved if a pump having 90% efficiency is used instead of a pump with 78% efficiency for this application.

Using

$$P = \frac{(Q \times \Delta P)}{(1000 \times \eta_p \times \eta_m)}$$

$$= \frac{(Q \times \Delta P)}{1000}\left(\frac{1}{\eta_{78\%}} - \frac{1}{\eta_{90\%}}\right)$$

$$= \frac{(0.08 \times 150 \times 10^3)}{1000}\left(\frac{1}{0.78} - \frac{1}{0.9}\right)$$

Saving = 2.05 kW

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Lifts

- Lifts account for about 5% of building energy consumption
- Lift motors are the main consumers
- Under certain operating conditions, lift motors can operates in regenerative mode
- Electrical consumption depend on factors such as the type of motor drive, the number of starts (door openings), carrying capacity, building height and building occupancy
- Data available from studies of lifts used in mid and high-rise buildings indicate that average consumption of lifts range from about 5 to 40 kWh/day

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Drive related energy saving measures

Type of lift

- Use traction type rather than hydraulic type as they consume 3 times as much energy

Type of drive

- Use latest drives such as VVVF
- Permanent magnet motors instead of induction motors (about 1 – 3% more efficient and don't require worm type gear reducers)

Use of regenerative energy

- Feedback regenerative energy into building distribution system rather than use resistors to dissipate as heat

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Other energy saving measures

Controls

- Use advanced algorithms to optimize energy usage in multiple lift applications

Lights & fans

- Use energy efficient systems and switch-off when not in use

Reduce capacity

- Where lift capacity is excessive, capacity can be downgraded and counterweights reduced

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LIGHTING SYSTEMS

LJ Energy Pte Ltd

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Content

- Introduction & definitions
- Types of lamps
- Lighting levels & lighting density
- Energy efficient lamps & ballast
- Lighting controls
- Lighting energy saving devices
- Daylighting

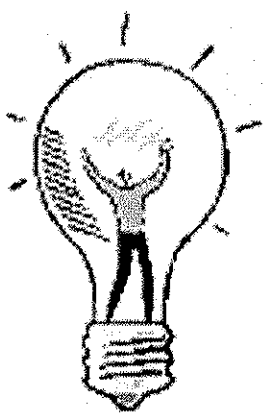
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Introduction

- Lighting accounts for about 20% of the electrical consumption in buildings
- Lighting also indirectly accounts for energy consumption in air-conditioned buildings
- However, lighting is essential for buildings to ensure comfort, productivity and safety of building occupants
- Therefore, lighting systems need to be carefully designed to achieve the desired illumination level while using the minimum amount of energy

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Luminous flux



Total quantity of light emitted by a light source per second

Unit = Lumens

Symbol = ϕ

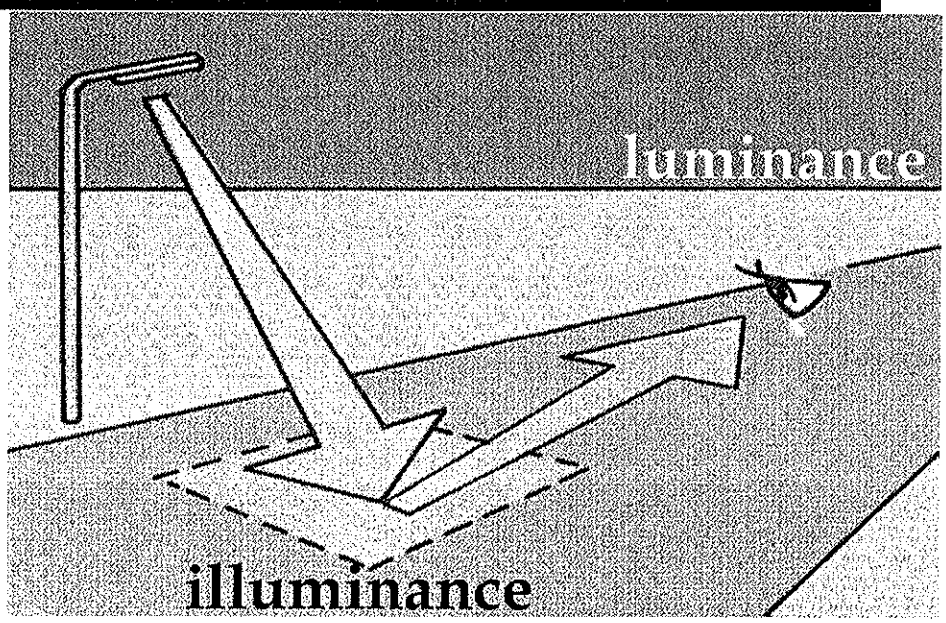
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Luminous flux

Lamp	Lamp Wattage	Lumens
Torch lamp	3 W	30
Incandescent lamp	75 W	950
Compact fluorescent lamp	15 W	810
Fluorescent lamp	36 W	2,400
High pressure sodium lamp	100 W	10,500
Low pressure sodium lamp	131 W	26,000

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Luminance



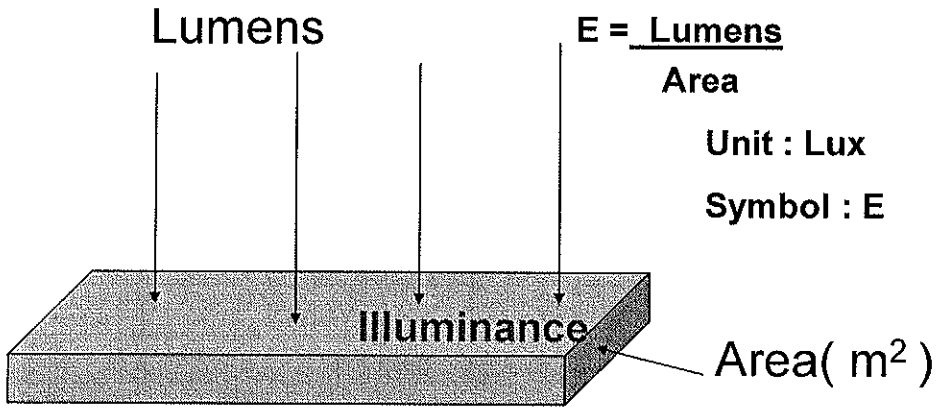
what you see

what you measured

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Illuminance

Luminous flux incident on a surface divided by the area of that surface : Also called Lighting Level



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Luminous efficacy

- **Luminous efficacy is the ratio of luminous flux emitted by a lamp to the power consumed by the lamp and its control gear**
- **This ratio indicates the efficiency of a lamp in converting electrical power into light**
- **The units of efficacy are lm/W**

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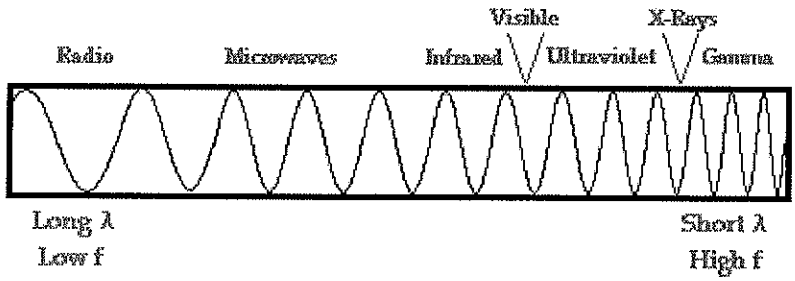
Luminous efficacy

Lamp type	Efficacy (lm/W)
Incandescent	10 - 15
Halogen	13 - 25
Compact fluorescent	50 - 60
Fluorescent tube	69 - 100
Metal halide	85 - 120
High pressure sodium	80 - 140
Low pressure sodium	150 - 200

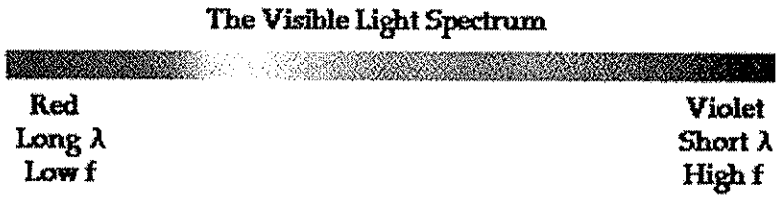
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Light spectrum

- Light is electromagnetic radiation



- Light is a very narrow wave band in the electromagnetic spectrum between 380 – 780 nm



- Creates the sensation of "vision" when it enters the eye

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Light spectrum (contd.)

Colour impression	Wave length (nm)
Red	630 - 780
Orange	600 - 630
Yellow	565 - 600
Green	500 - 565
Blue	435 - 500
Violet	380 - 435

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Colour temperature

- The colour temperature of a light source is a numerical measurement of its colour appearance
- It is based on the fact that when an object is heated to a temperature high enough it will emit light and as the temperature is increased, the colour of the light emitted will also increase
- Colour temperature is defined as the temperature of a blackbody radiator which emits radiation of the same chromaticity as the lamp
- The unit of colour temperature is Kelvin (K)

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Colour temperature (contd.)

- The degree of "warmth" or "coolness" of the space is related to the colour temperature of the light source
- The lower the colour temperature, the "warmer" the light appears
- Light sources that appear violet or blue colour are "cool" while those that are red, yellow or orange are "warm"

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Colour temperature (contd.)

Lamp type	Colour temperature (K)
Incandescent filament lamp	2600 - 3000
Tungsten Halogen	3000 - 3400
Warm white fluorescent	3000
Cool white fluorescent	4000
Day light fluorescent	5000
Metal halide	3300 - 5700
High pressure sodium	2000 - 3200
Low pressure sodium	1600

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Colour rendering

- While colour temperature is a measure of the colour of a light source, colour rendering index is an indication of the ability of a light source to accurately show colours
- Colour rendering expresses the appearance of object colours when illuminated by a given light source as compared with their appearance from a reference light source
- It is usually expressed as an index called colour rendering index (CRI) which is an indication of the appearance of an object illuminated by light source compared to the appearance under natural light

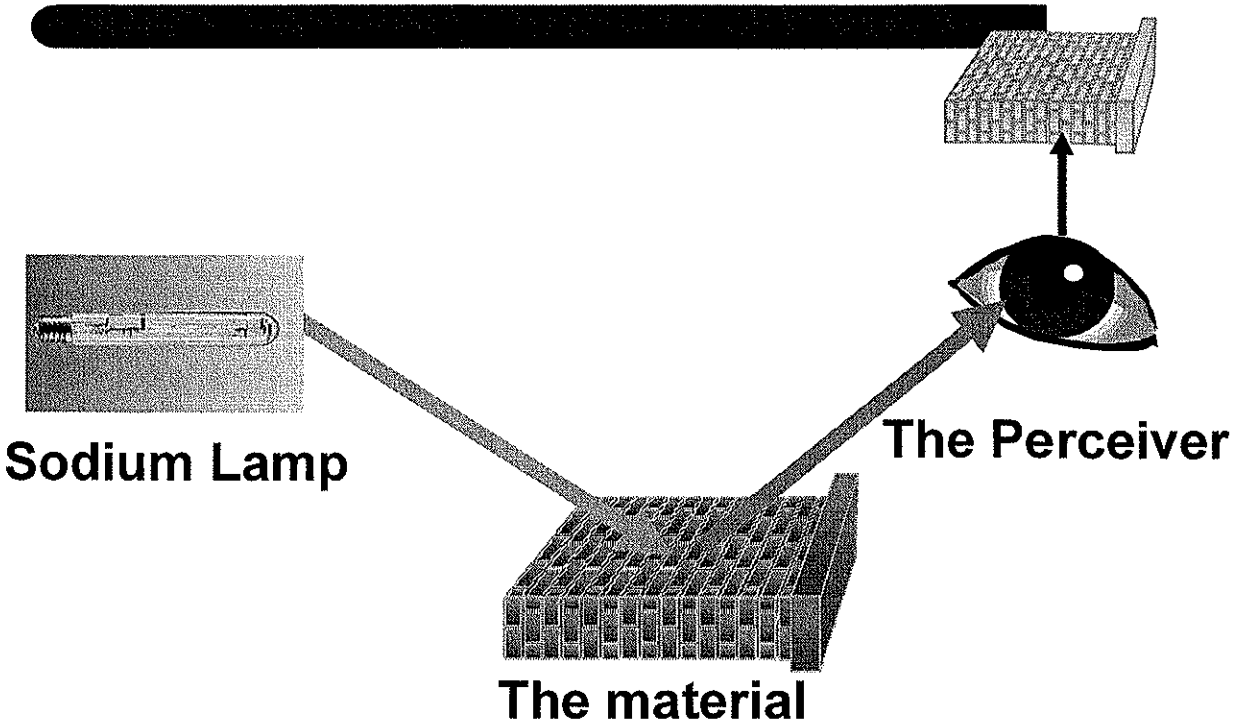
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Colour rendering (contd.)

- Natural light will have a CRI of 100
- Electric filament lamps produce a continuous spectrum with all colours present and therefore they have a CRI of 100
- Normally CRI below 80 is considered poor colour rendering while CRI above 80 is considered good

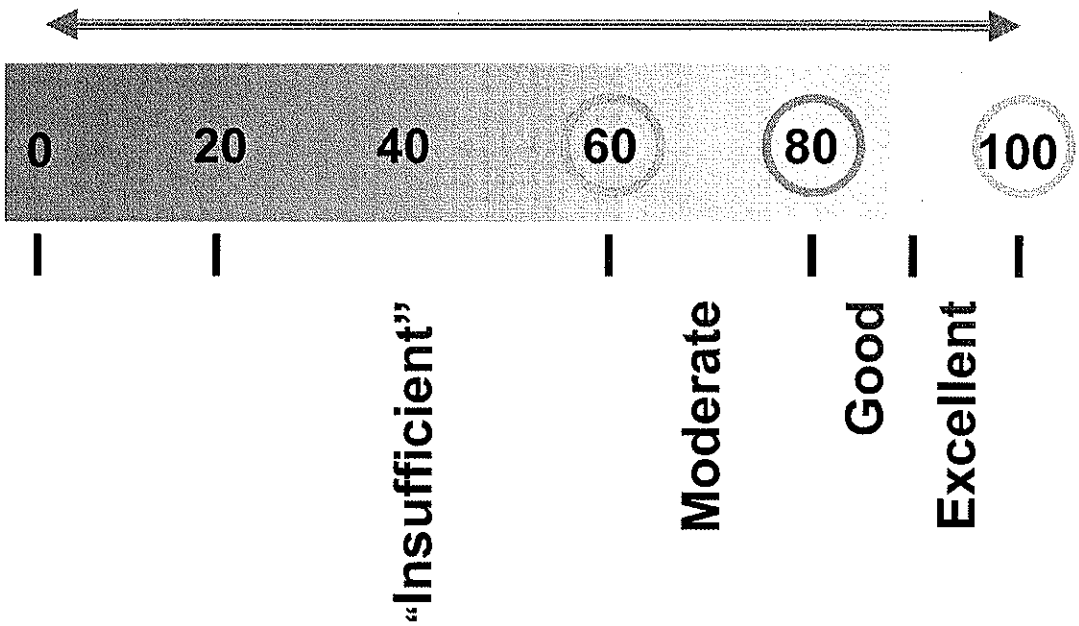
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Colour rendering (contd.)



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Practical interpretation of CRI



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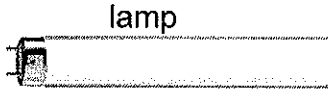
Colour rendering (contd.)

Lamp type	Colour rendering index (CRI)
Incandescent filament lamp	100
Tungsten Halogen	100
Fluorescent	80 - 95
Metal halide	65 - 80
High pressure sodium	25
Low pressure sodium	0

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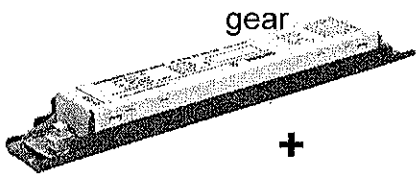
Components of lighting systems

lamp



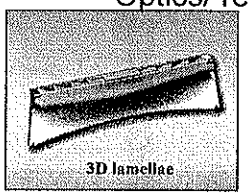
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gear



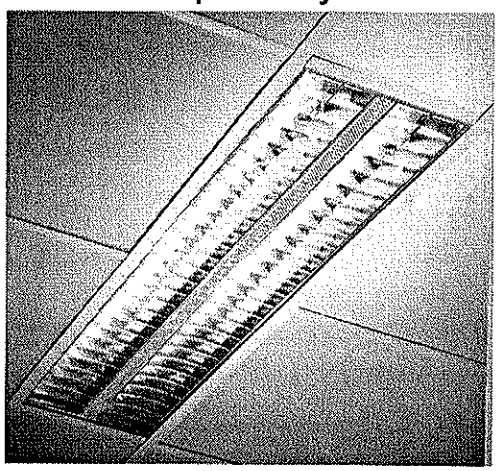
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Optics/ reflector



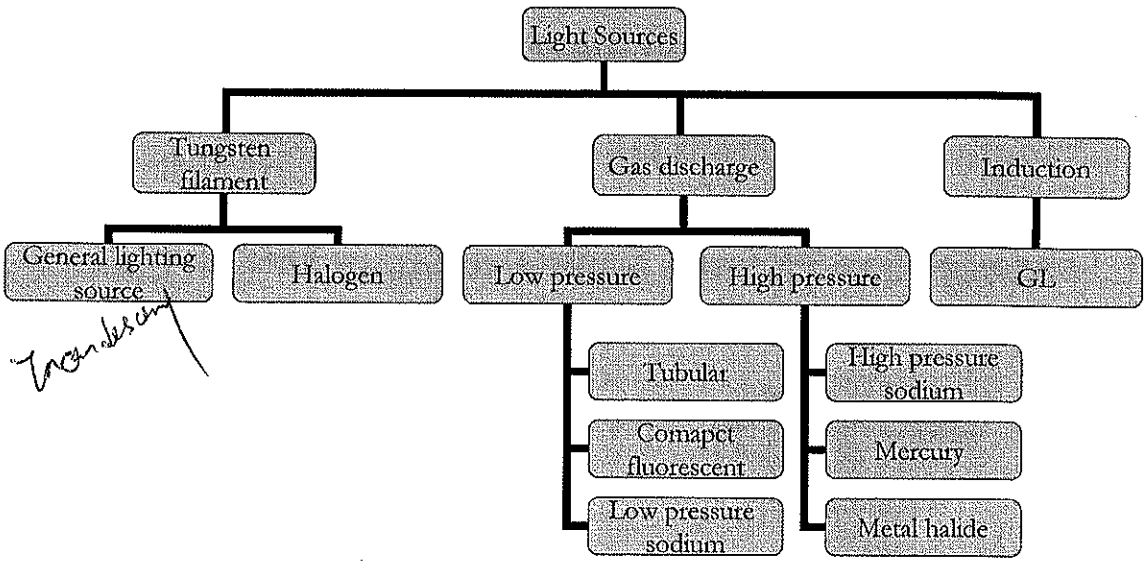
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Complete system



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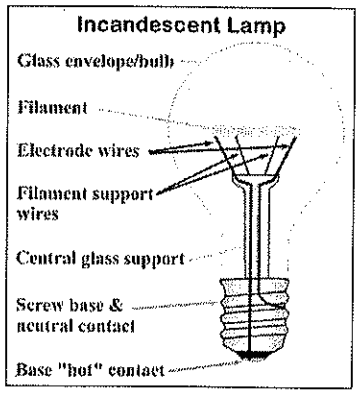
Light sources



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Filament lamps

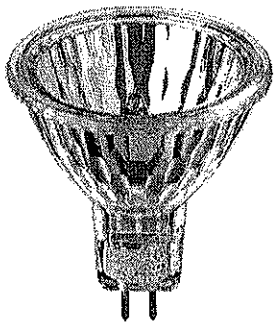
- Light is produced by an incandescent filament (tungsten) sealed in a glass bulb usually containing an inert gas
- Low initial cost
- Good colour rendering (above 95)
- Good lumen maintenance
- Can be dimmed
- Low efficacy – 10 to 15 lm/W (92% of energy converted to heat and only 8% converted to light)
- Relatively shorter life (about 1000 hrs)



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Filament lamps - Halogen

- Halogen lamps have halogen added to prevent evaporated tungsten blackening the bulb and thus ensures excellent lumen maintenance
- Light from halogen lamps is more "sparkling"
- Halogen lamps have slightly higher efficacy of about 13 to 25 lm/W (converts about 88% to heat energy)



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Fluorescent lamps

- In fluorescent lamps, an arc is created between two electrodes in a tube filled which ionizes a gas or vapour (Mercury)
- The ionization releases electromagnetic radiation in the ultra violet region
- Light output comes from phosphor coating which is activated by the ultra violet energy of the discharge
- Higher efficacy than filament lamps

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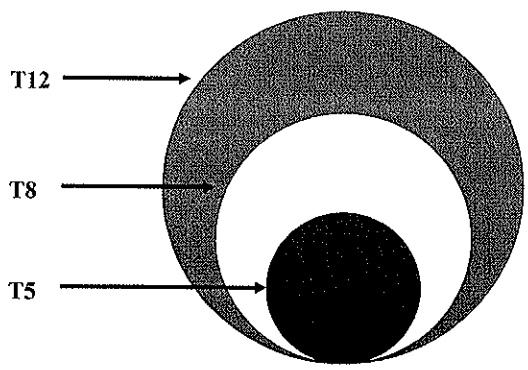
Linear fluorescent lamps

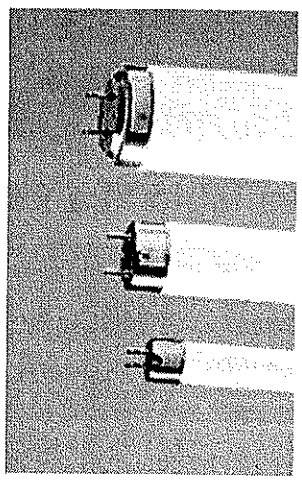
- They are one of the most common types of lamps used for general lighting
- They come in varying lengths
- The tubes are classified by a "T" number which refers to the tube diameter
- The colour rendering index for linear fluorescent lamps is normally about 70 to 80
- The lamp life is about 12,000 hours which is much more than the life of filament lamps

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Sizes of fluorescent lamps

- Typical length are: 1 ft, 2 ft., 3ft.,4 ft., 5ft. and 6 ft. lamps
- Typical diameters:





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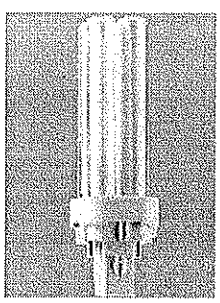
Efficacy of tubular fluorescent lamps

Year	Type	Efficacy	Tube diameter	Consumption
	1st generation	50 lm/W	38 mm	
1973	2nd generation T12	69 lm/W	38 mm	40W
1978	3rd generation T8	93 lm/W	26 mm	36W conv. ballast
1982	4th generation T8	100 lm/W	26 mm	32W electronic ballast
1995	T5 (needs new fittings – reduced diameter & length)	104 lm/W	16 mm	28W

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Compact fluorescent lamps (CFLs)

- Quick and easy replacement for typical screw-base incandescent lamps
- Consumes only about 20% to 25% of the energy consumed by incandescent lamps
- Life about 8,000 hours (compared to 1000 hrs for filament lamps)
- Costs more than incandescent lamps
- Available in a variety of shapes



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Comparison of incandescent and CFLs

Incandescent	40W	60W	75W	100W
CFL	9W	11W	15W	20W

- Energy saving
- Longer life
- Less maintenance cost

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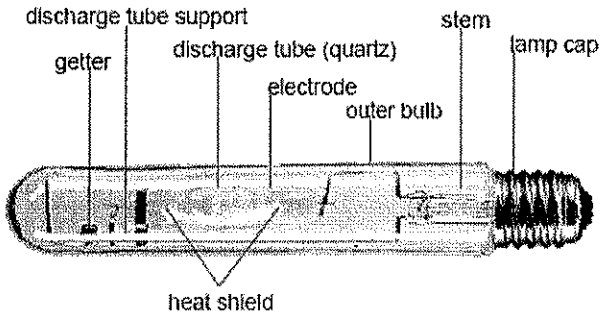
HID lamps

- Better efficacy than fluorescent lamps
- Longer life than fluorescent lamps
- Types are metal halide, mercury vapour and high pressure sodium lamps
- Useful for high-bay lighting for industrial environments, outdoor flood lighting and roadway lighting

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Metal halide

- Consists of an arc tube (quartz or ceramic) within an outer envelope (glass)
- Arc tube contains argon, mercury and halogen(iodine)
- The high voltage provided by the ballast ionises the argon. The heat produced vaporises the mercury & halogen to emit light
- High efficacy
- High quality lighting (CRI about 70)
- Used for swimming pool, tennis court, stadium and high-bay lighting



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Mercury vapour

- Consists of an inner arc tube filled with argon and a drop of mercury and electrodes
- When electricity passes through the arc, mercury vaporises emitting UV light which glows the fluorescent material coated on the inside of the outer tube
- They have an efficacy of about 30 to 55 lm/W which is lower than other HID lamps
- Low initial cost
- Longer life & colour stability

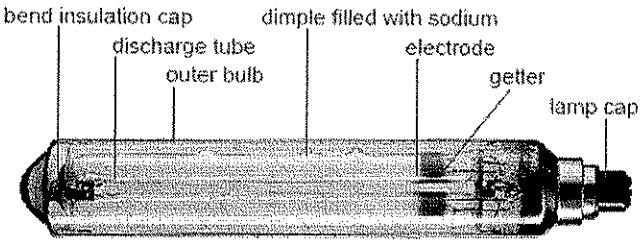
Cheap Cost Effective

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Low pressure sodium lamps

yellow

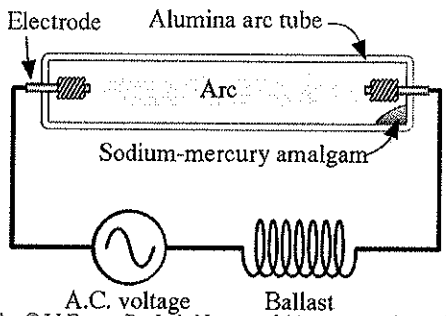
- Consists of a U-shaped arc tube containing metallic sodium and an inert gas such as neon
- The arc vaporises the metallic sodium to produces light only in the yellow part of the spectrum (monochromatic)
- Highest efficacy of all lamps
- Mainly used for street lighting (foggy climates), tunnel entrances (colour adaptation) and security lighting

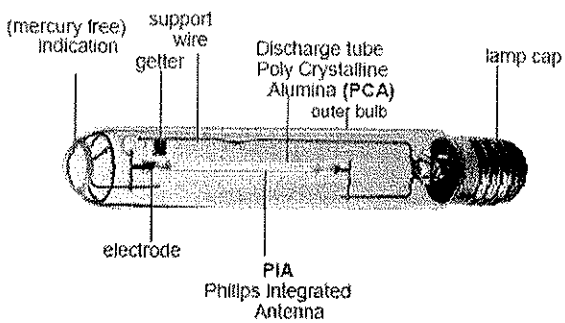


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High pressure sodium

- Arc tube with sodium-mercury amalgam and electrodes
- Due to the higher pressure, pressure broadening and self absorption occurs to making the lamp non-monochromatic
- Higher efficacy than metal halide and mercury lamps
- Lower CRI (better than low pressure sodium)
- Used for street and high-bay applications

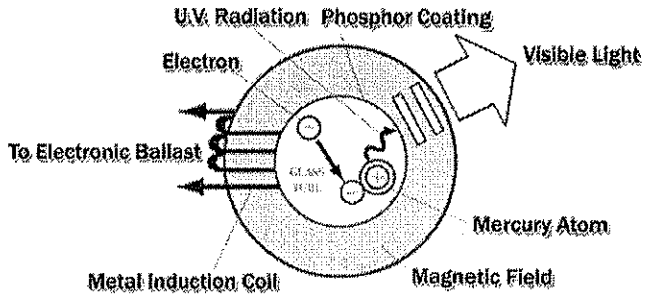




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Induction lamps

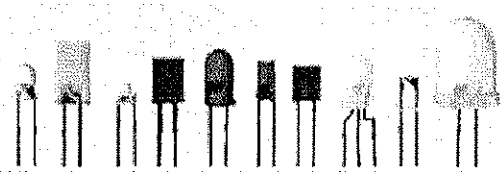
- An external coil is used to create a magnetic field which can penetrate through the glass and excite the mercury inside the tube
- The mercury emits UV light which is converted to visible light by the phosphor coating
- Since the coil is external, the generated heat can be easily dissipated
- Exceptionally long life (eg. 100,000 hours) as there are no electrodes or filaments



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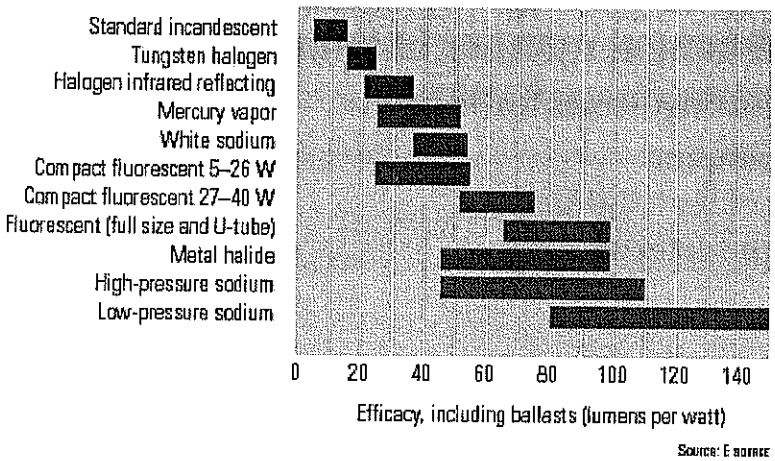
LEDs

- Light emitting diodes are semiconductor diodes with p-n junctions
- Current flows from p to n
- Electrons flow across the junction and when they encounter "holes", the energy level drops and emit photons (light)
- LEDs are made of different materials to produce different colours (red, blue, green etc.)
- White light is made by mixing colours or using blue LEDs with phosphor coating



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Summary of lamps and efficacy



Source: E source

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Recommended lighting levels

- **The lighting level required for a space depends on the type of space, tasks performed in the space and other visual requirements**
- **SS 531**

Type of area	Recommended value (lux)
General offices, conference rooms, computer work stations	500
School classrooms	300
Shops, departmental stores	500
Theatres	200
Lobbies, corridors	150
Hotel s: Reception Corridors	 300 100
Car parks: Parking areas In/out ramps	 75 300 (day) 75 (night)

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Reducing lighting levels

- For new installations, this can be achieved through good lighting design by optimizing factors such as type of lamps, number of lamps and lamp spacing
- For existing installations:
  - De-lamping
  - Use of task lighting
  - Lamp replacement

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Maximum permissible lighting loads

- The amount of electricity used for lighting depends on the type of lighting used (efficacy) and other lighting design criteria such as the type of luminaries used, location and spacing of luminaries and whether reflectors or covers are used
- The overall efficiency of a lighting design can be evaluated using the lighting power allowance (or lighting power density) which is computed in W/m^2 or W/ft^2

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Maximum permissible lighting loads

Description	Maximum lighting power budget based on SS 530 (W/m^2)
Offices and class rooms	15
Lecture theatres	15
Auditoriums/Concert halls	10
Shops/Supermarket/Departmental stores	25
Restaurants	15
Lobbies/Atriums/Concourses	10
Stairs	6
Corridors	10
Car parks	5
Electronic manufacturing and fine detail/assembly industries	20
Medium & heavy industries	15
Warehouse / storage areas	10

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Achieving lighting power density

- **Lighting design**
- **Use of higher efficacy lamps**
  - **CFL in place of filament lamps**
  - **T5 instead of T8 & T12**
  - **Using HID lamps for high-bay applications**
  - **Using LEDs**
- **High efficiency ballast**

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Incandescent vs CFLs

- Incandescent lamps have a low efficacy of about 10 to 15 lm/W and therefore are not energy efficient
- They can be easily replaced with compact fluorescent lamps (CFL) which have a much higher efficacy of about 50 to 60 lm/W

Incandescent	40W	60W	75W	100W
CFL	9W	11W	15W	20W

- Compact fluorescent lamps also have a life span of about 8 times that of incandescent lamps (8000 hours compared to 1000 hours).

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Linear fluorescent lamps

Linear fluorescent T8 to T5

- Increased efficacy of 93 to 104 lm/W
- Need to replace fixture or use adaptor

2 feet Tubes	4 feet Tubes
T8 tube 22 W (18 + 4)	T8 tube 40 W (36 + 4)
T5 tube 15 W (14 + 1)	T5 tube 28 W (27 + 1)

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Example - Linear fluorescent lamps

Calculate the simple payback period for replacing 100 nos. of 600mm (2 feet) long T8 lamps with T5 lamps costing $30 each if they operate 24 hours a day, 7 days a week and the electricity tariff is $0.20 / kWh .

Power consumption of the lamps:

	T8	T5
Power consumption of lamp & ballast (W)	22	15

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Example – (contd.)

Energy savings per lamp = (22 – 15) = 7 W

Energy savings per day = (7 x 100 x 24)/1000 kWh

= 16.8 kWh/day

Annual savings = 16.8 x 365 x $0.2 = $1,226.40

Total cost = $30 x 100 = $3,000

Payback period = 3,000 / 1,226.40 = 2.4 years

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Example - Linear fluorescent lamps

Calculate the simple payback period for replacing 100 nos. of 1200mm (4 feet) long T8 lamps with LED lamps costing $70 each if they operate 24 hours a day, 7 days a week and the electricity tariff is $0.20 / kWh .

Power consumption of the lamps:

	T8	LED
Power consumption of lamp & ballast (W)	40	18

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Example – (contd.)

Energy savings per lamp = (40 – 18) = 22 W

Energy savings per day = (22 x 100 x 24)/1000 kWh

= 52.8 kWh/day

Annual savings = 52.8 x 365 x $0.2 = $3,854

Total cost = $70 x 100 = $7,000

Payback period = 7,000 / 3,854 = 1.8 years

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High-bay lamps

- For high-bay lighting applications such as warehouses, factories, large stores and sports facilities, metal halide and high pressure sodium lamps should be used instead of mercury vapour lamps
- Similarly for outdoor lighting, metal halides, high pressure sodium and where acceptable, low pressure sodium lamps can be used

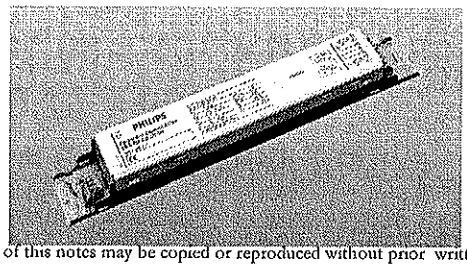
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Ballast (control gear)

Fluorescent and HID lamps require ballast to control the voltage and current

Types of ballast

- Conventional magnetic ballast have core & coil assemblies
- Electronic ballast have electronic components to convert the 50Hz input power to output of 20-60kHz. This makes power to light conversion more efficient



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Ballast (contd.)

Ballast losses

- **Ballast use energy during operation which is called ballast losses**
- **Magnetic ballast have the highest losses and electronic ballast are about 30% more energy efficient**

Lamp Watts	Control gear	Losses
40W	Standard EM	12 W
36 W	Standard EM	8 W
36 W	Low loss EM	6 W
36 W	HF electronic	4 W
28 W	HF electronic	3 W

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Example - ballast

Calculate the simple payback period for replacing 100 nos. of magnetic ballast with electronic ballast if they operate 24 hours a day, 7 days a week and if the electricity tariff is $0.10 / kWh.

Take the unit cost of electronic ballast to be $20 (supply & installation) and the saving in power consumption to be 4 W per lamp.

Energy savings per day	**= (4 x 100 x 24)/1000 kWh**
	= 9.6 kWh/day
Annual energy savings	**= 9.6 x 365 x $0.10 = $350.40**
Total cost of ballast	**= $20 x 100 = $2,000**
Payback period	**= 2,000 / 350.40 = 5.7 years**

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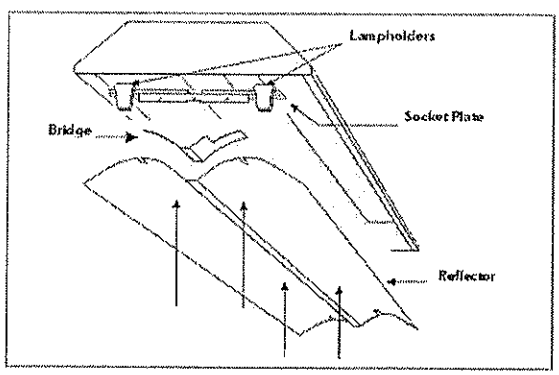
Luminaire optical efficiency

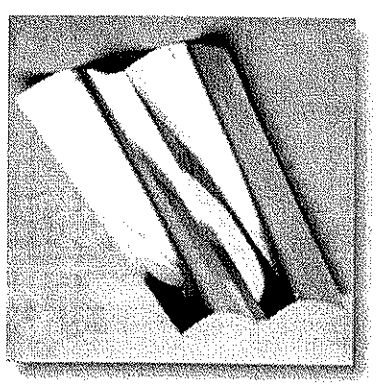
- Due to the cylindrical shape of the linear fluorescent lamps, if reflectors are not used, about half of the light emitted by them would be reflected on to the ceiling
- Therefore, various types of reflectors are used to improve the optical efficiency of luminaries used for linear fluorescent lamps
- Most standard reflectors used in luminaries of fluorescent lamps have a reflectivity of about 70 to 80%

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Luminaire optical efficiency (contd.)

- Special reflector materials are anodized, specular aluminum having a total reflectivity of 85 to 90 percent and vacuum-deposited, specular silver applied on a polyester surface having a total reflectivity of 91 to 95 percent
- Ideal for converting 4 lamp fixtures to 2 lamp fixtures (50% saving)





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Lighting controls

- **Timers - to switch on / off lighting according to occupancy schedules**
- **Light sensors - when daylight increases, lights can be automatically dimmed or switched off**
- **Occupancy sensors - to ensure lamps are switched off when areas are not occupied. Can be infrared type, ultrasonic type or combined.**
  - Toilets
  - Car parks
  - Meeting rooms
  - Storage rooms
  - Corridors

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Daylighting

- **Designing to use natural lighting instead of artificial lighting**
- **Using natural lighting to supplement artificial lighting**
- **Using devices to transmit natural light to interior zones**

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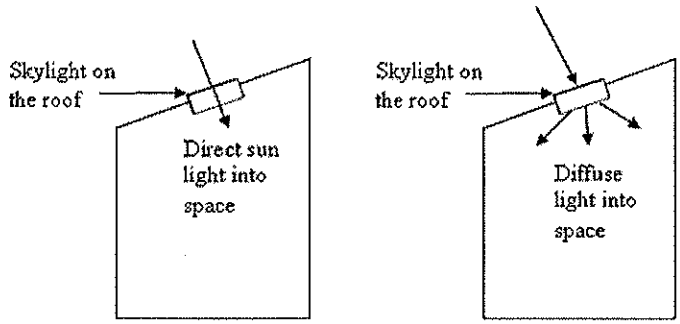
Daylighting (contd.)

Windows

- To bring daylight into perimeter areas of buildings
- Amount of daylight depends on window area, orientation, material properties, shading etc.

Skylights

- To bring daylight through the roof of buildings
- Light can be direct or diffuse (using special materials)

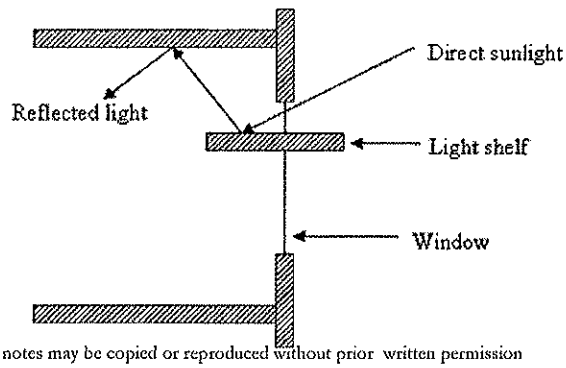


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Daylighting (contd.)

Light shelves

- Passive architectural feature consisting of a horizontal reflecting surface
- They help to prevent direct sunlight from entering a space by reflecting sunlight onto the ceiling thereby minimizing glare and increasing the lighting level
- They work best at high solar angles but can be extended inwards at low angles to capture the direct rays

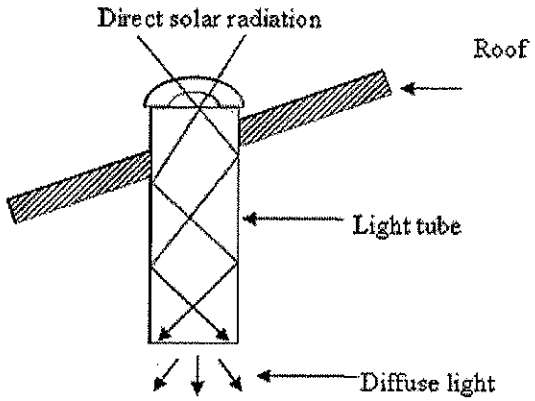


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Daylighting (contd.)

Light pipes

- Light tubes and light pipes have internally light reflecting surfaces that help to transmit natural light into the interior spaces of buildings to minimise the use of artificial lighting



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Summary

- Introduction & definitions
- Types of lamps
- Lighting levels & lighting density
- Energy efficient lamps & ballast
- Lighting controls
- Lighting energy saving devices
- Daylighting

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