# OPTIMIZATION OF ENERGY SYSTEMS
## Module Code: ESP4401

***AY2022/2023: Semester-2***

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# Objectives and Learning Outcomes



- **Prepare students professionally ready** for energy conscious design and efficient operation of major energy consuming systems used in industries and commercial buildings.
- **Module contents:** Similar to "**S**ingapore **C**ertified **E**nergy **M**anager, **SCEM**" course.
- Prepare students for **SCEM** and **E**nergy **E**fficiency **O**pportunities **A**ssessor **(EEOA)**.
- Students will see the **relevance and application** of their engineering **knowledge** to **real-world situations**.
- **Thinking and application of engineering knowledge**. Not long derivation of formulas.
- Students will gain the experience of **handling real-world energy related engineering challenges in classroom environment**.

# Objectives and Learning Outcomes



**Learning outcomes:**

- Analyze performance of major energy consuming systems
- Identify energy and cost saving opportunities
- Concept design of energy efficient systems based on actual energy consumption behavior of industrial processes
- Develop control / energy performance enhancement strategies
- Analyze technical and economic feasibility of energy optimization options

# Major Topics and Schedule



**Class schedule:**

1) Central Air-conditioning systems: 5 weeks
2) Boiler system: 1.5 weeks
3) Combined heat and power (CHP) system: 2.5 weeks
4) Compressed air system: 1.5 weeks
5) Energy management system: 0.5 week
6) Financial analysis of energy projects: 1 week
7) Revision and discussion: 1 week

**Workload:** Lecture/Class: 3 hrs/week
Assignment/Tutorial/Seminar: 1 hr/week
Preparatory work: 6 hrs/week

# Assessments



**1. Practice problems: 5% marks**
Few practice problems / cause-and-effect questions will be given every week $\Rightarrow$ Online multiple submissions.

**2. Attendance: 5% marks** (-0.5 mark for 1 absence without valid reasons)

**3. Class test: 20% marks**
Multiple-choice, short calculation, brief explanation on cause-and-effect.

**4. Assignment: 20% marks**
Take-home assignment on selection of Combined Heat and Power (CHP) plant to support the demands of electricity, steam and chilled water of an industrial plant.
Submission type: Group submission

**5. Final Examination: 50% marks**

Closed book examination - mainly on: (a) Solving of energy related problems and analysis of results, (b) Explanation of operation and control strategies, cause-and-effect, etc.

# Reading List



- Heating, Ventilating and Air Conditioning Analysis and Design, F.C. McQuiston, J.D. Parker, J.D. Spitler
- Steam Plant Operation, E.B. Woodruff, H.B. Lammers, T.F. Lammers,
- Compressed air systems: a guidebook on energy and cost savings, Talbott, E.M.
- Air-Conditioning & Mechanical Ventilation Systems. Reference Manual – SCEM. IES & NEA. Md Raisul Islam.

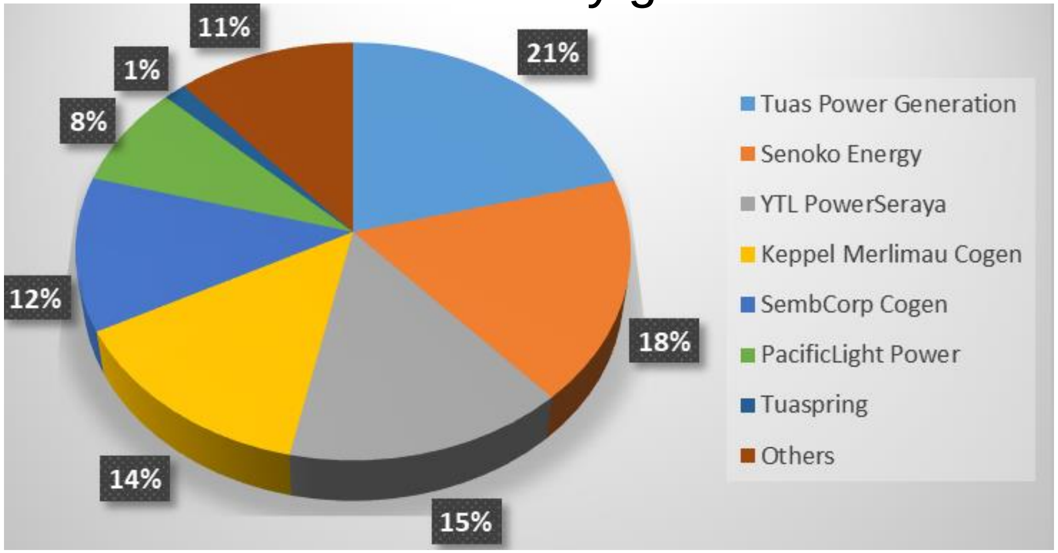
https://www.ies.org.sg/Tenant/C0000005/PDF%20File/Registry/SCEM/ACMV(1).pdf

# Singapore Energy Resources

**Singapore main energy resources are:**

- Electricity
- Liquefied Natural Gas
- Natural Gas
- Town gas
- Oil
- Solar photovoltaic systems

Market share of electricity generation



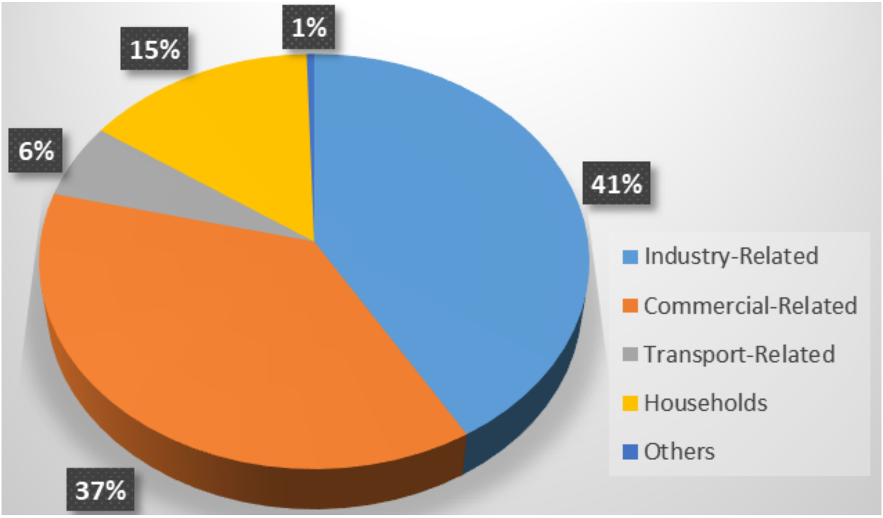

Others: Wholesale Licensees, Waste-To-Energy Plants and Solar PV units.

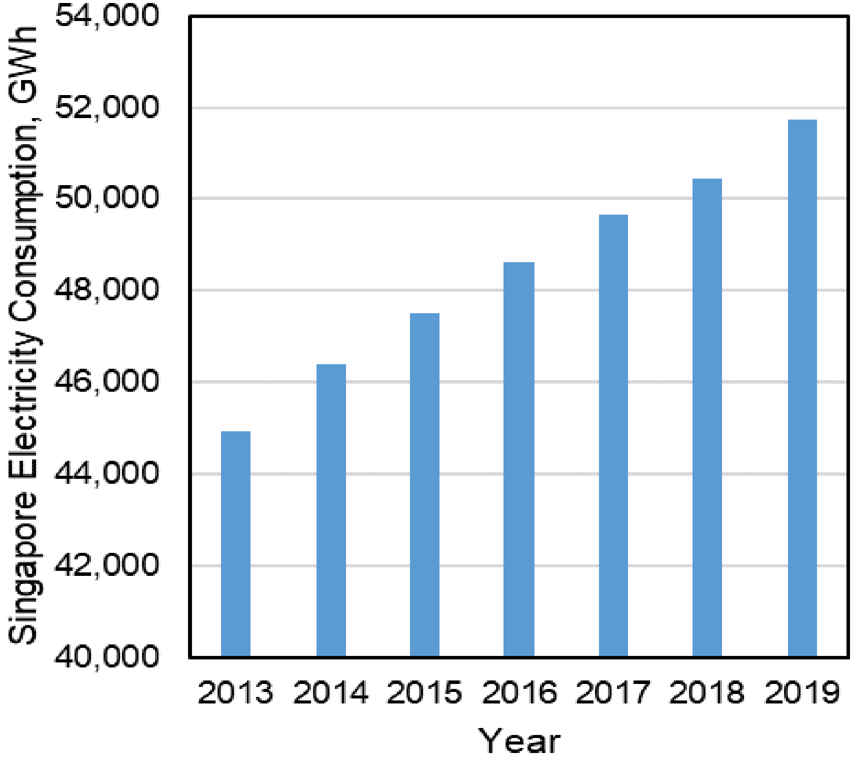
- Average electricity generation efficiency of Singapore power plants is about 45%
- Singapore electricity grid emission factor is about 0.45 kg $CO_2$/kWh

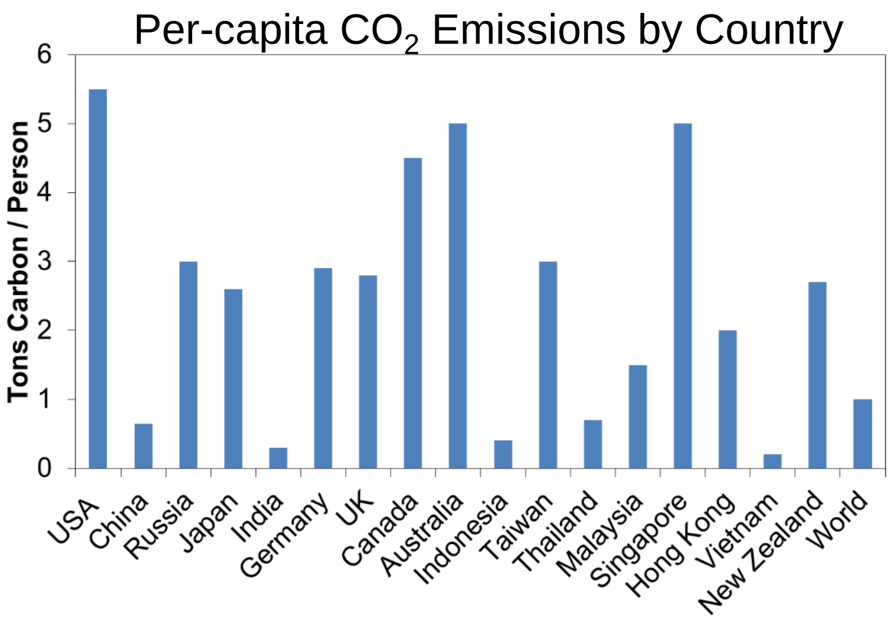
*Source: Energy Market Authority (EMA)*

# Electricity Consumption in Singapore





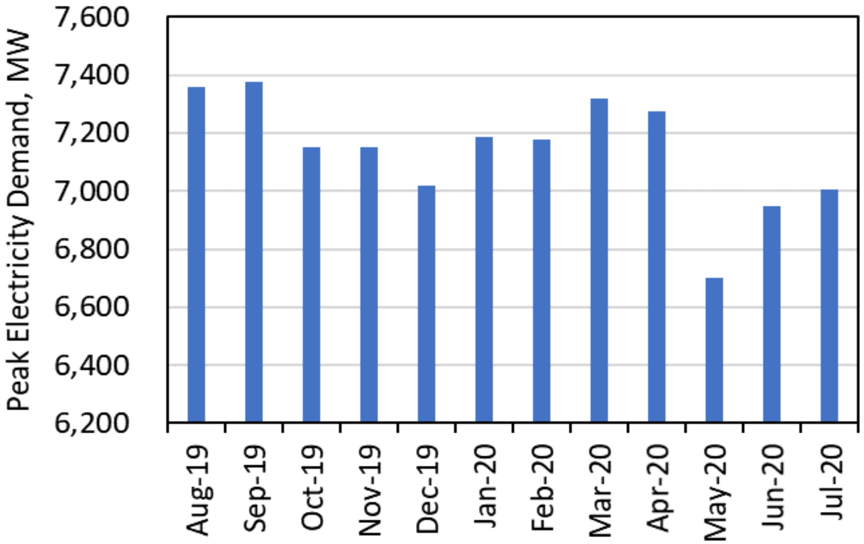




*Source: Energy Market Authority (EMA)*

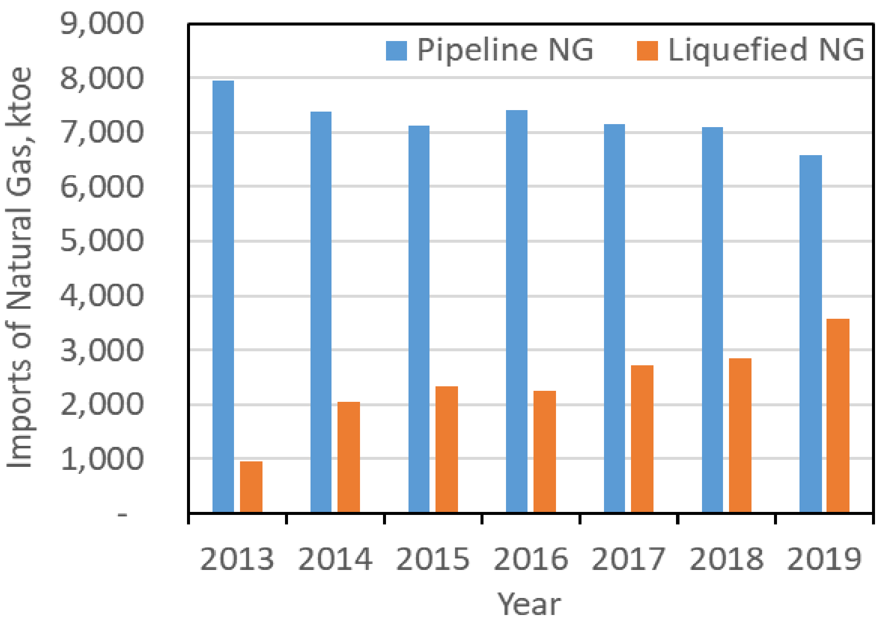
# Electricity Demand and Production Capacity






Electricity Generation Capacity by Technology Type

| | Year 2019 | Year 2020 |
|---|---|---|
| **Total Generation Capacity, MW** | **12,562.8** | **12,582.0** |
| CCGT/Co-Gen/Tri-Gen, MW | 10,491.4 | 10,491.4 |
| Steam Turbine, MW | 1,363.6 | 1,363.6 |
| Open Cycle Gas Turbine, MW | 180.0 | 180.0 |
| Waste-To-Energy, MW | 256.8 | 256.8 |
| Solar PV, MW | 271.0 | 290.2 |




Annual Fuel Mix for Electricity Generation

| | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|
| Petroleum Products, % | 0.7 | 0.6 | 0.4 | 0.2 |
| Natural Gas, % | 95.2 | 95.4 | 95.6 | 96.0 |
| Coal, % | 1.3 | 1.3 | 1.2 | 1.0 |
| Others, % | 2.9 | 2.8 | 2.8 | 2.8 |

Others: Wholesale Licensees, Waste-To-Energy Plants and Solar PV units

1 tonne of oil equivalent (toe) = 41.868 GJ = 11,630 kWh

*Source: Energy Market Authority (EMA)*

# Singapore Natural Gas Supply System



- Natural Gas (NG) is the key energy resource for Singapore. Most of NG has been imported from Indonesia and Malaysia through pipelines

- About 95% electricity is generated using NG in Singapore

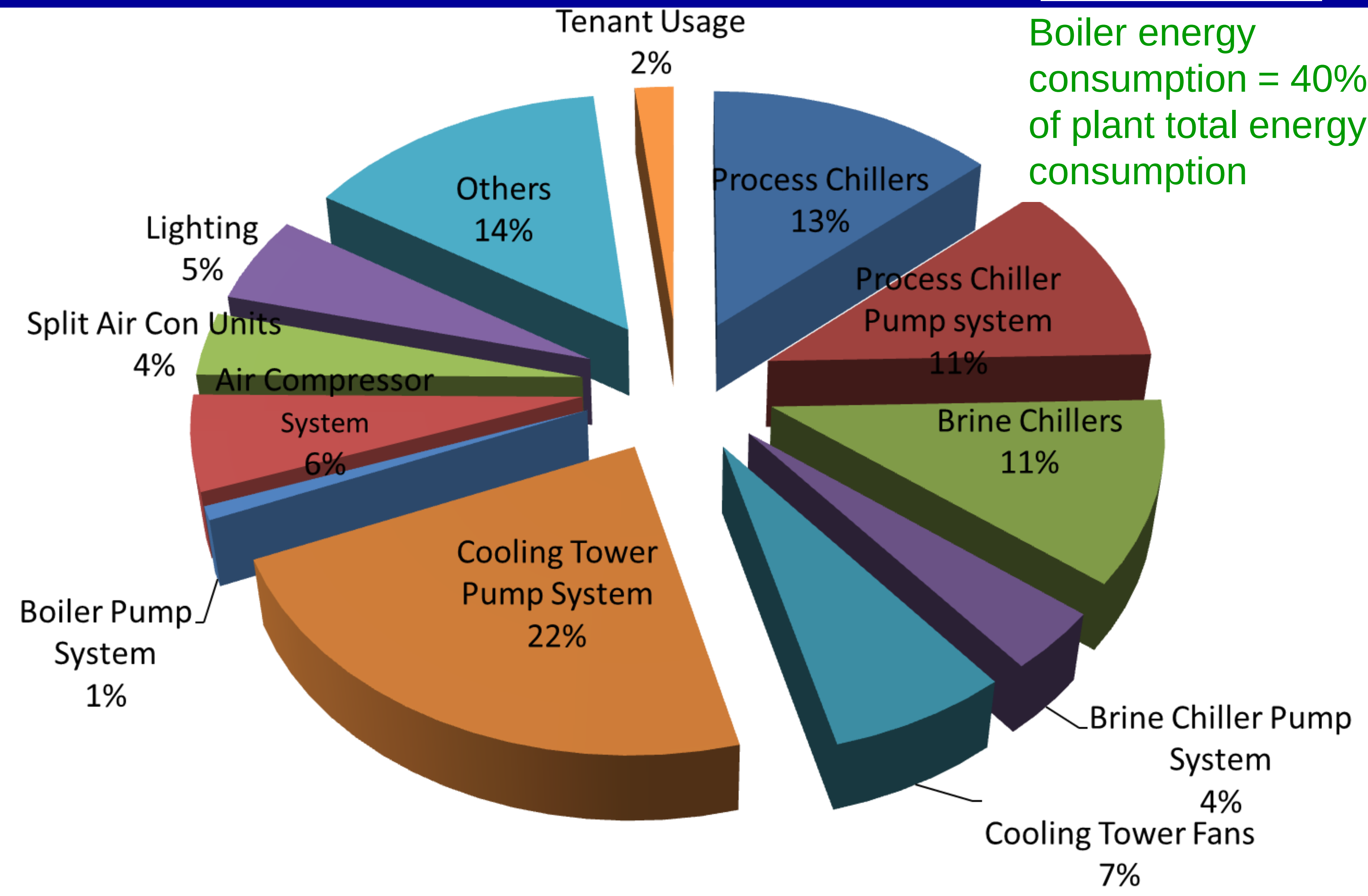
- Two separate gas pipeline networks in Singapore – One is for town gas that is mainly used for cooking and heating by residential and commercial customers. The other is for NG that is mainly used for electricity generation and industrial feedstock

- Since May 2013, Singapore has started importing Liquefied Natural Gas (LNG, $\approx$ -170$^{o}$C) to diversify and secure its energy sources

- LNG can be more easily transported using ships rather than pipelines. LNG can be imported from all around the world.

# Energy Consumption Breakdown of a Chemical Industry

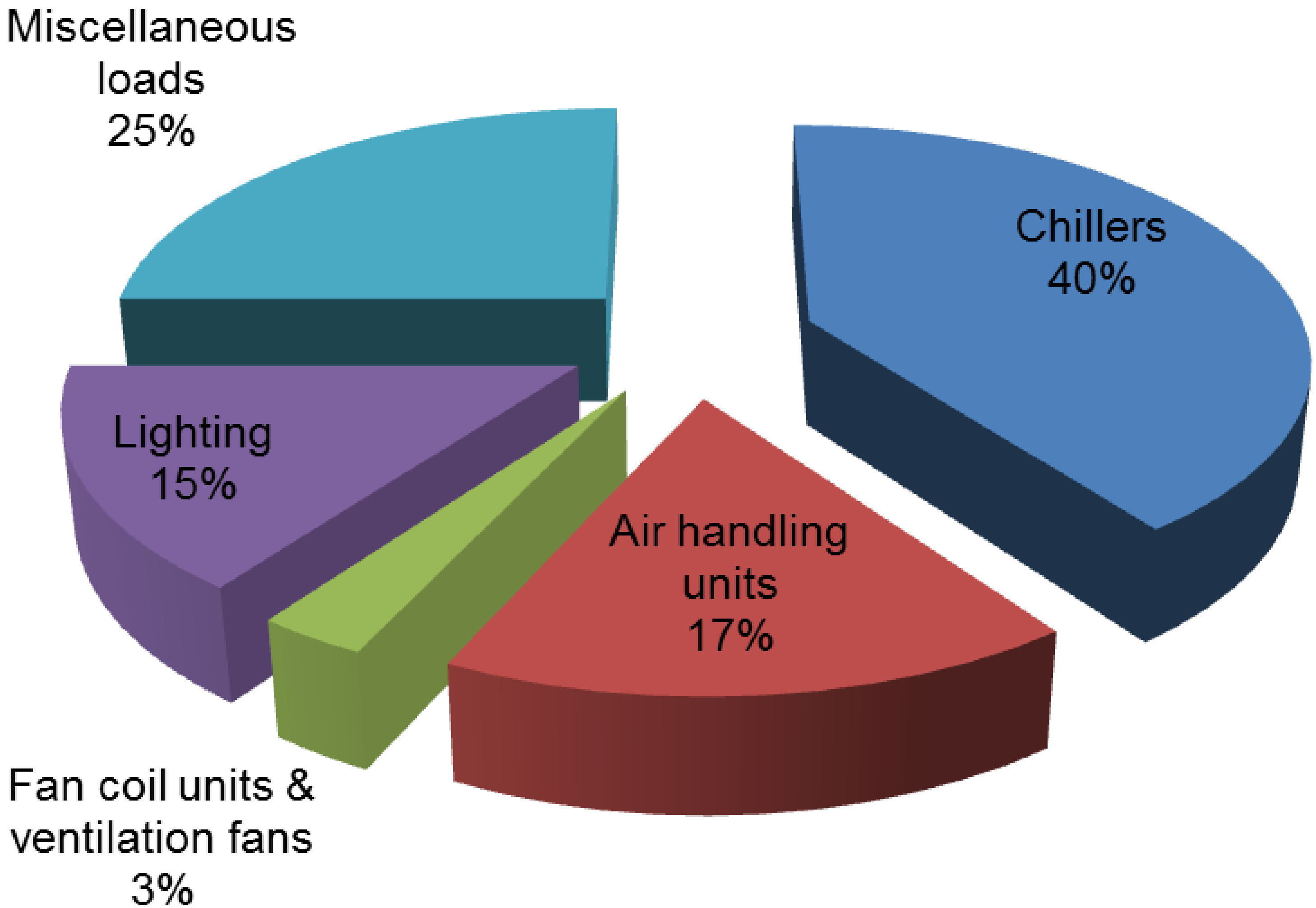





Boiler energy consumption = 40% of plant total energy consumption

# Electric Energy Consumption Breakdown of a Typical Commercial Building






- ➢ Air Conditioning and Mechanical Ventilation (ACMV) system is the biggest consumer (about 60%) of electricity in buildings

# Singapore Sustainable Blueprint



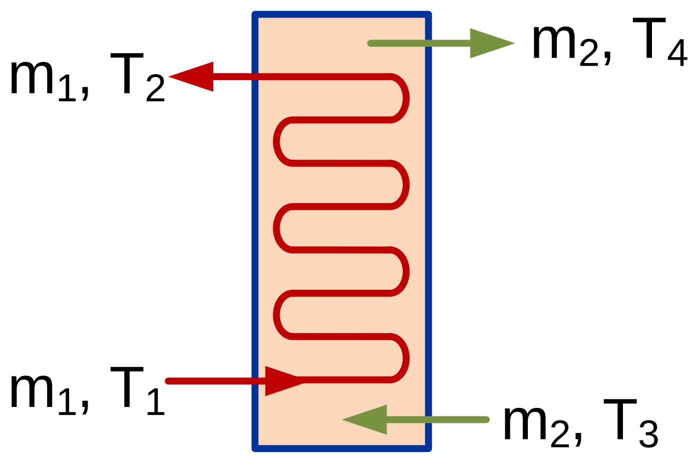
- Singapore Government has set a target to achieve **35% improvement** in energy efficiency from the 2005 level by 2030
- Singapore has targeted to trim its carbon emissions by 16% below 2020 business-as-usual levels
- Recently, Singapore Government has introduced mandatory energy management requirements for large energy users which consume more than **15 GWh under an Energy Conservation Act**. These include the **appointment of Energy Managers**, reporting of energy use and submission of energy efficiency improvement plans

➢ **E**nergy **E**fficiency **O**pportunities **A**ssessment (**EEOA**) for Registered Corporations and New Ventures.

https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/energy-efficiency/industrial-sector/energy-efficiency-opportunities-assessment-for-registered-corporations

# Conservation of Energy and Mass

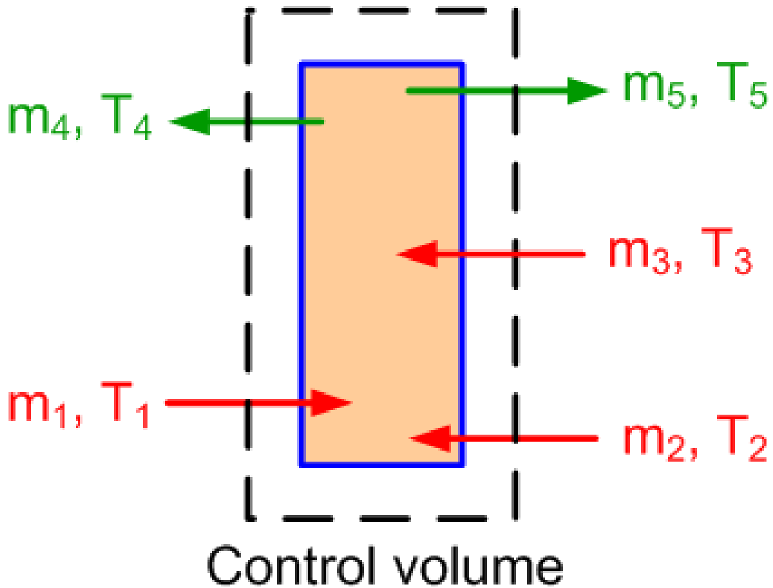





**Energy conservation law:**

**Heat gain = Heat reject** $Q_1 = Q_2$

$m_1 \times C_{p1} \times (T_1 - T_2) = m_2 \times C_{p2} \times (T_4 - T_3)$




**Conservation of energy:**

Incoming energy = Outgoing energy

$m_1 \times C_{p1} \times T_1 + m_2 \times C_{p2} \times T_2 + m_3 \times C_{p3} \times T_3$

$= m_4 \times C_{p4} \times T_4 + m_5 \times C_{p5} \times T_5$

**Conservation of mass:**

Incoming mass = Outgoing mass

$m_1 + m_2 + m_3 = m_4 + m_5$

# Singapore Sustainable Blueprint



- Singapore Government has set a target to achieve **35% improvement** in energy efficiency from the 2005 level by 2030

Suppose, annual electricity consumption for an industry = **15 GWh/year**

Suppose electricity tariff = $0.25/kWh

Monthly electricity bill = 312,500 $/month

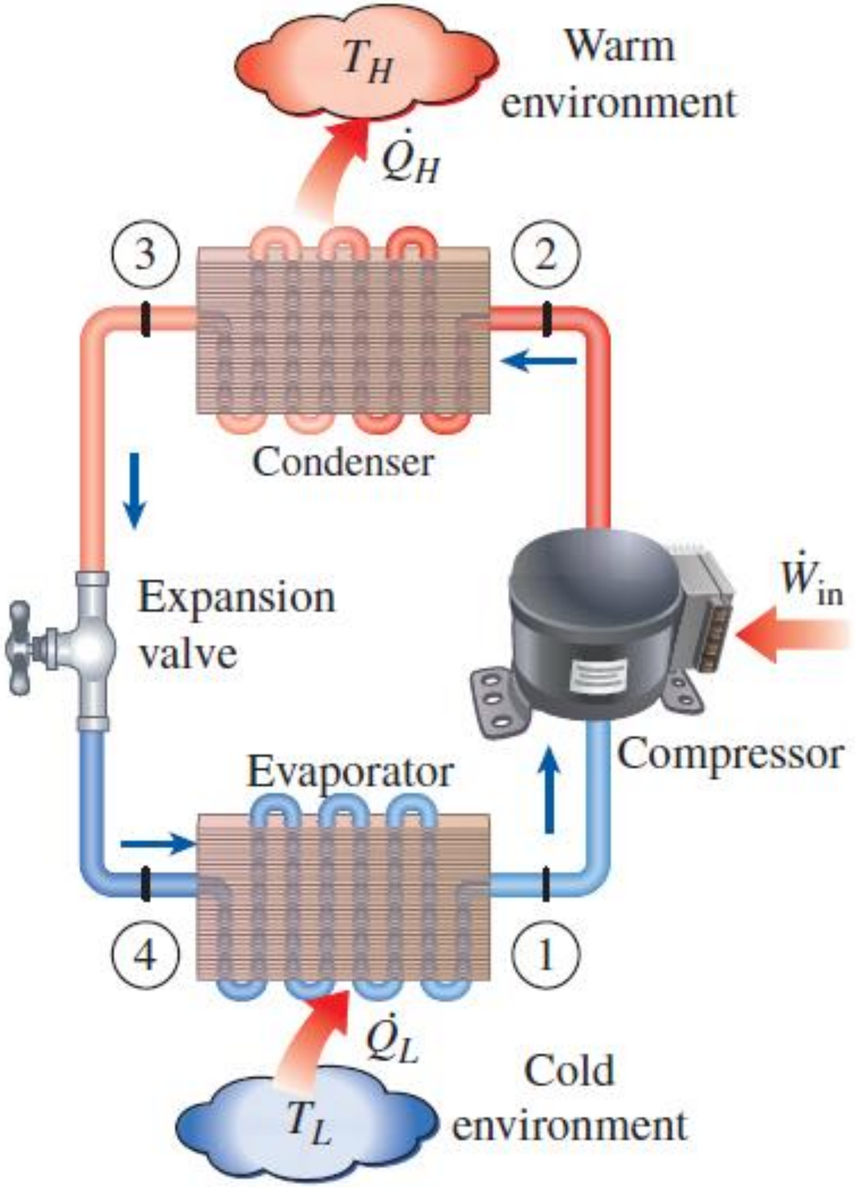
Assume **10% energy savings** after optimization of energy systems

Electric energy saving = **125,000 kWh/month**

Energy cost saving = 125,000x0.25 = **$31,250 /month = $375,000 /year**

# ENERGY EFFICIENT
# AIR-CONDITIONING SYSTEMS

# Main Components of Air-Conditioning System

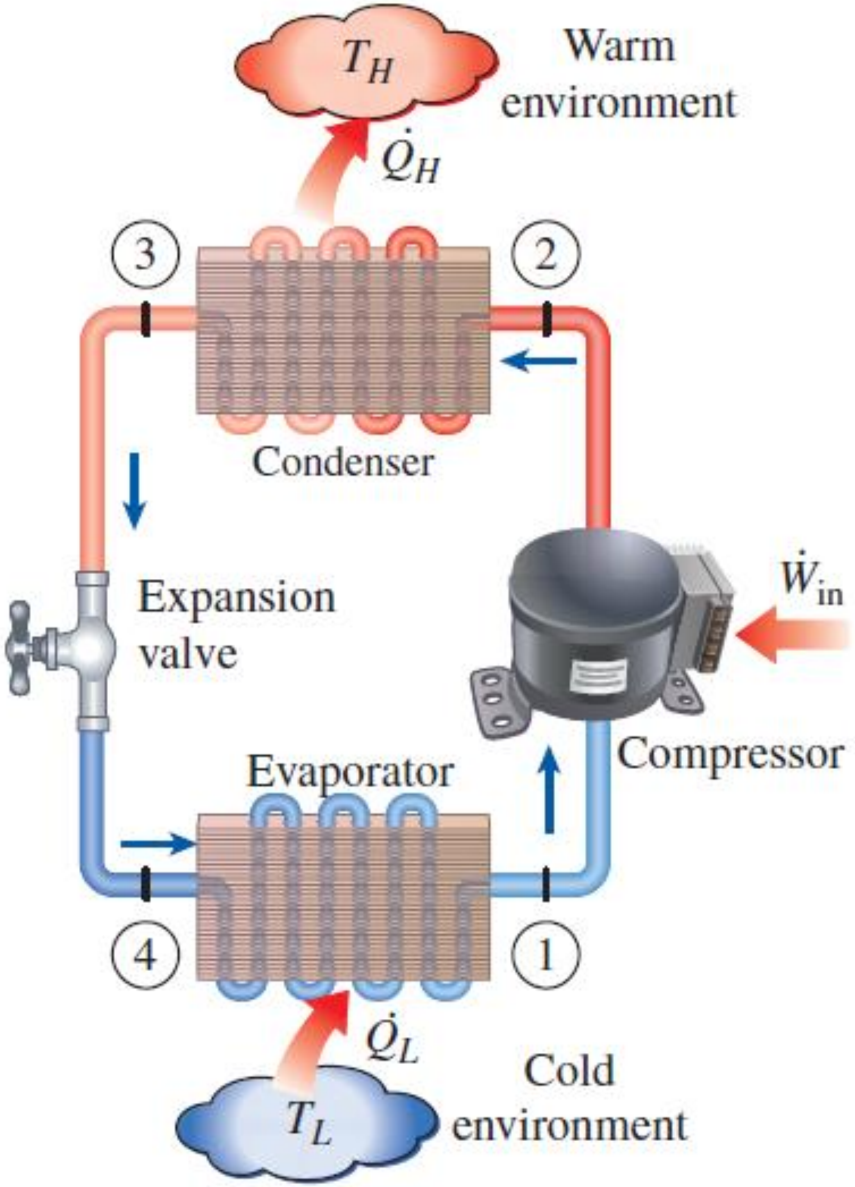


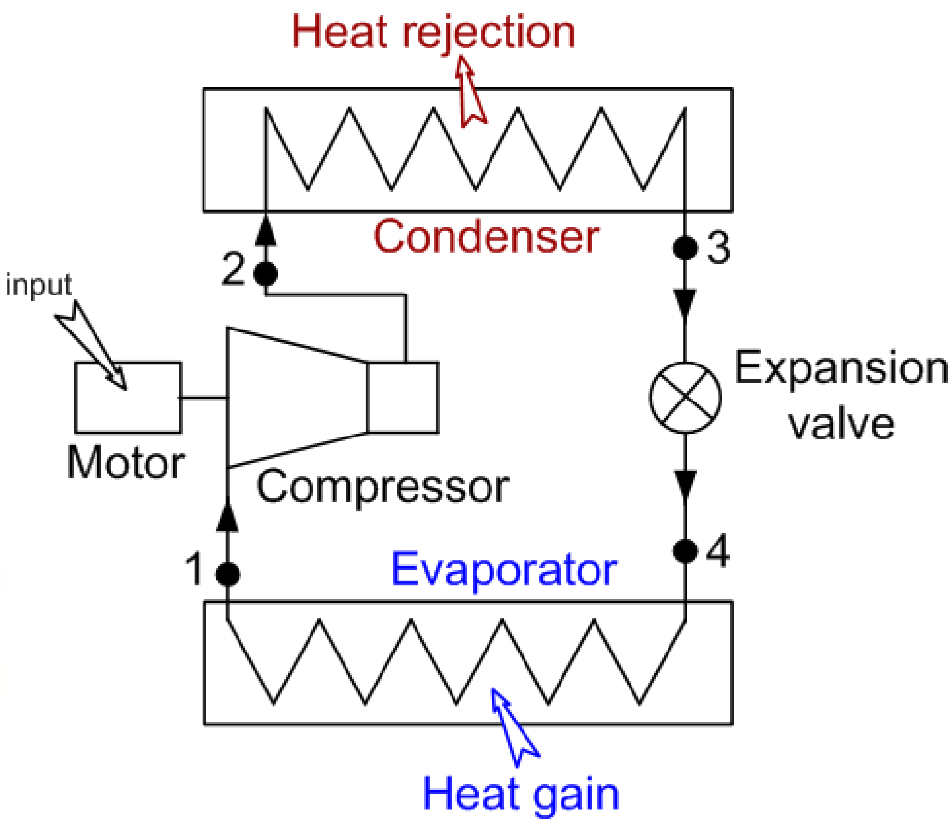

**Main components:**

1) Compressor: to increase pressure of refrigerant vapor. Compressor is connected with a motor which consumes electrical energy.
2) Condenser: a heat exchanger for rejecting heat from refrigerant vapor.
3) Expansion valve: to reduce pressure of liquid refrigerant
4) Evaporator: a heat exchanger for absorbing heat from surrounding air or circulating water.

# Main Components of Air-Conditioning System



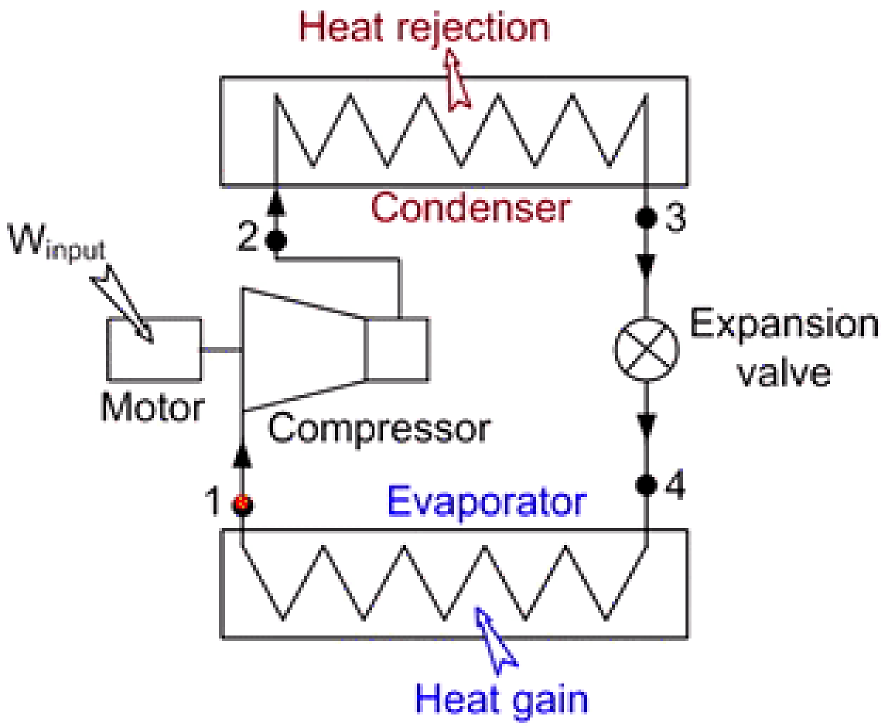


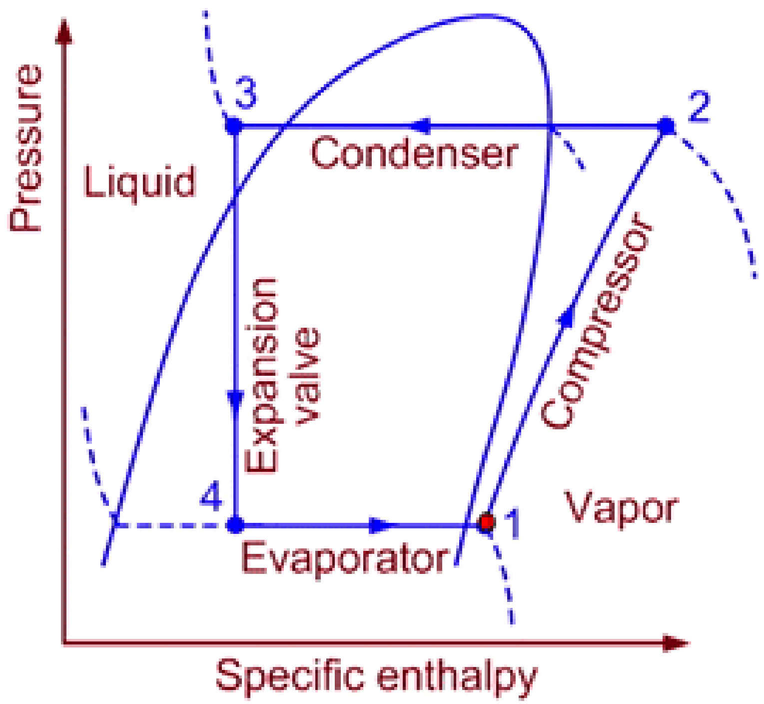




- Fluid flowing through the system is called refrigerant
- Refrigerant changes its phase at different stages of the system

# Main Components of Air-Conditioning System






Point-1: Refrigerant in vapor phase, P is low, T is low

Point-2: Refrigerant in vapor phase, P is high, T is high

Point-3: Refrigerant in liquid phase, P is high, T is high. Point- 2 to 3: heat rejection process. Refrigerant convert from vapor to liquid

Point-4: Refrigerant is liquid & vapor mixture, P is low, T is low. Point- 4 to 1: heat absorption process. Refrigerant convert from liquid to vapor

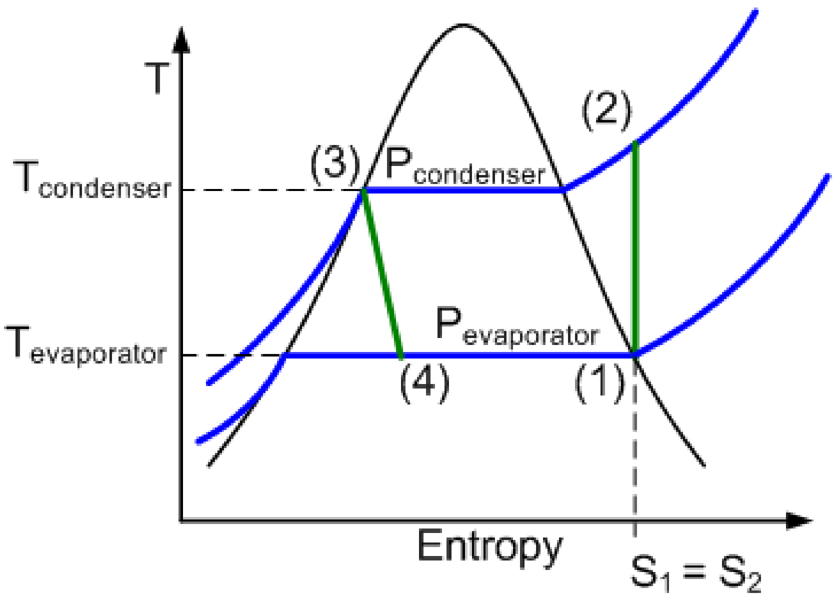
# Problem

**Problem:** A process cooler uses refrigerant-R134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between evaporator pressure of 0.14 MPa and condenser pressure of 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine: (a) the rate of heat removal from the process and the power input into the compressor, (b) the rate of heat rejection to the environment and (c) the cycle efficiency kW/RT and the COP of the cooler. Draw P-h and T-s diagram for the refrigeration cycle with operating parameters.

**Solution:**

**Point-1:** $P_1 = 0.14$ MPa, Saturated
From R-134a table: $h_1 = h_g = 236.04$kJ/kg
$s_1 = s_g = 0.9322$ kJ/kg K

**Point-2:** $P_2 = 0.8$ MPa, $s_2 = s_1$
From R-134a table: $h_2 = 272.05$ kJ/kg



# Problem

**Point-3:** $P_3 = 0.8$ MPa
From R-134a table:
$h_3 = h_{f@0.8MPa} = 93.42$ kJ/kg

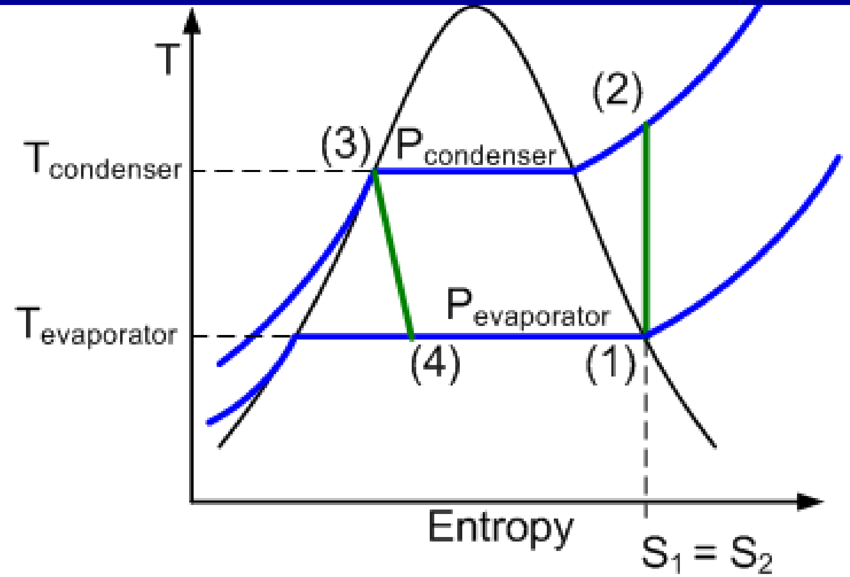
**Point-4:**
$h_4 = h_3 = 93.42$ kJ/kg

(a) $Q_{evap} = m_r(h_1 - h_4)$
$= 0.05(236.04 - 93.42) = 7.13$ kW

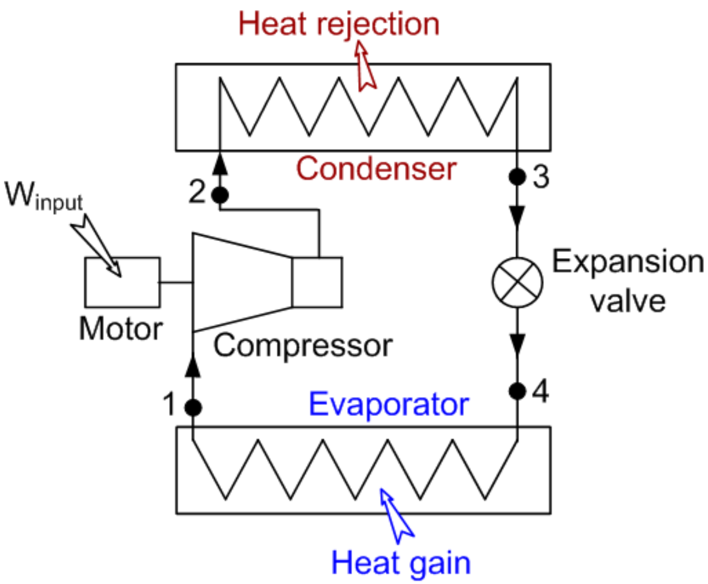
$W_{in} = m_r(h_2 - h_1) = 0.05(272.05 - 236.04)$
$= 1.8$ kW

(b) $Q_{cond} = m_r(h_2 - h_3)$
$= 0.05(272.05 - 93.42) = 8.93$ kW

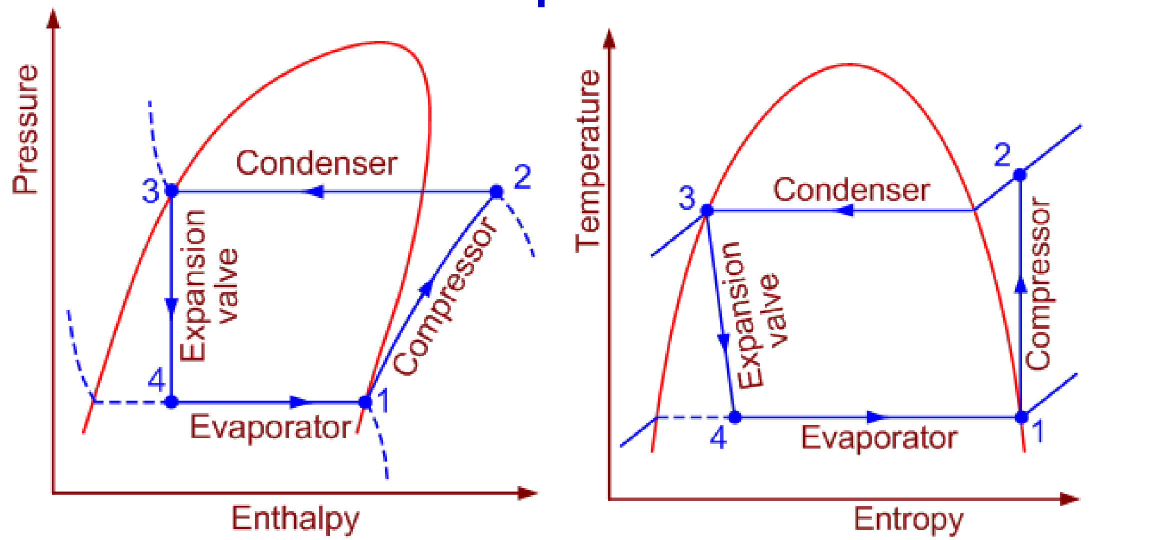
(c) $COP = Q_{evap} / W_{in} = 7.13/1.8 = 3.96$



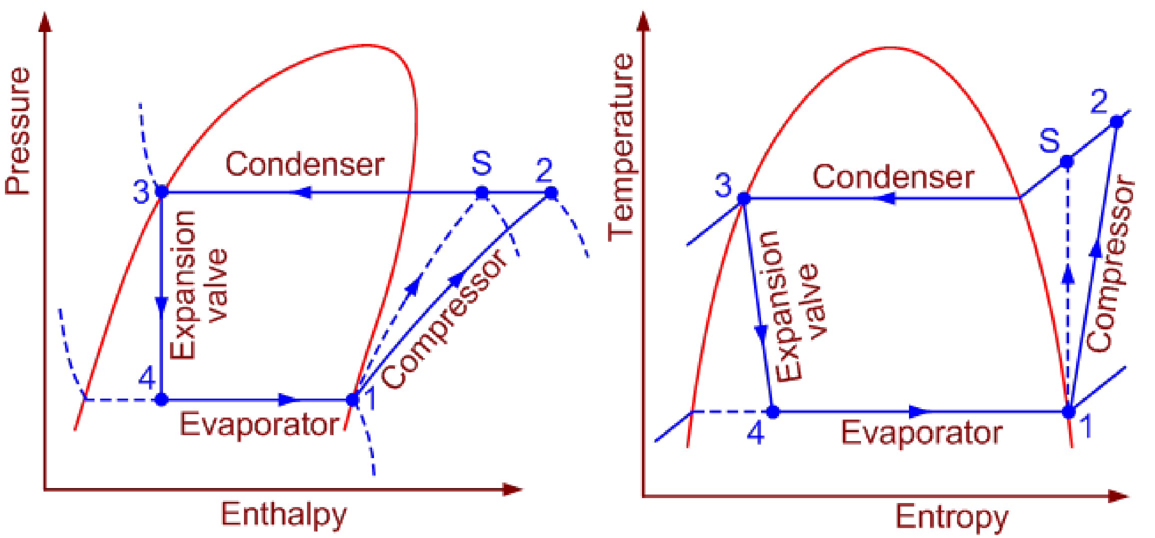
# Isentropic and Actual Processes




## Isentropic Process




## Actual Process




**Isentropic efficiency:**

$$\eta_c = \frac{h_s - h_1}{h_2 - h_1}$$

# Problem



**Problem:** Refrigerant-R134a enters the compressor of a process cooler as superheated vapor at 0.14 MPa and -10$^{o}$C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50$^{o}$C. The refrigerant is cooled in the condenser to 26$^{o}$C and 0.72 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, determine: (a) the rate of heat removal from the process and the power input into the compressor, (b) the isentropic efficiency of the compressor and (c) the cycle efficiency kW/RT and the COP of the cooler. Draw P-h and T-s diagram for the refrigeration cycle with operating parameters. Compare the performance of the cooler of previous problem.

# Problem

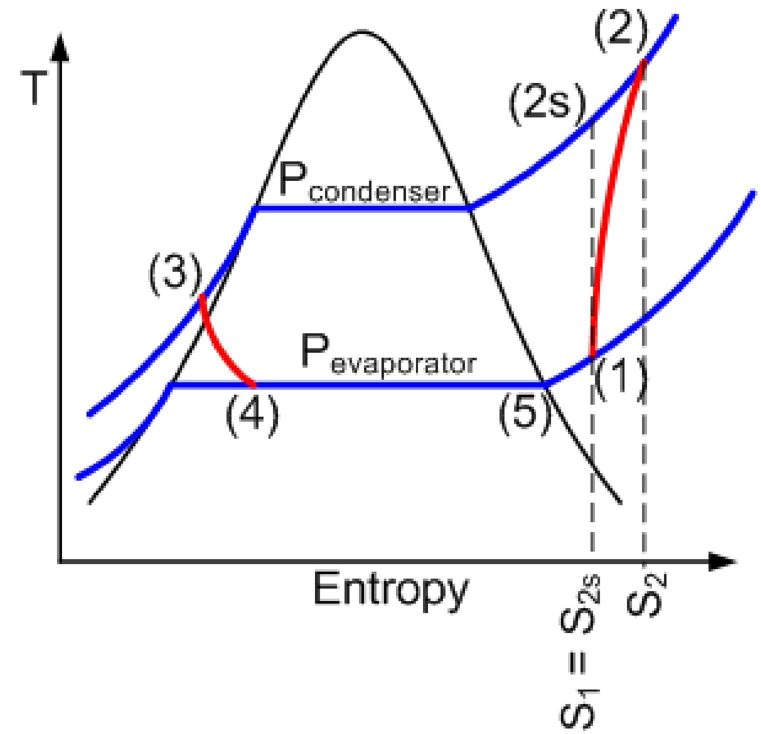


**Solution:** **Point-1:** $P_1 = 0.14$ MPa, $T_1 = -10^oC$
From R-134a table: $h_1 = 243.4$ kJ/kg
$s_1 = 0.9606$ kJ/kg K

**Point-2:** $P_2 = 0.8$ MPa, $T_2 = 50^oC$
From R-134a table: $h_2 = 284.39$ kJ/kg

**Point-3:** $P_3 = 0.72$ MPa, $T_3 = 26^oC$
From R-134a table: $h_{f@26C} = 85.75$ kJ/kg

**Point-4:**
$h_4 = h_3 = 85.75$ kJ/kg




(a) $Q_{evap} = m_r(h_1 - h_4)$
$= 0.05(243.4 - 85.75) = 7.88$ kW
$= 7.88/3.517 = 2.24$ RT

$W_{in} = m_r(h_2 - h_1)$
$= 0.05(284.39 - 243.4) = 2.05$ kW

(b) $P_2 = 0.8$ MPa, $s_{2s} = s_1 = 0.9606$ kJ/kg K, From R-134a table: $h_{2s} = 281.05$ kJ/kg

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{281.05 - 243.4}{284.39 - 243.4} = 0.919$$

(c) COP = $Q_{evap} / W_{in} = 7.88/2.05 = 3.84$

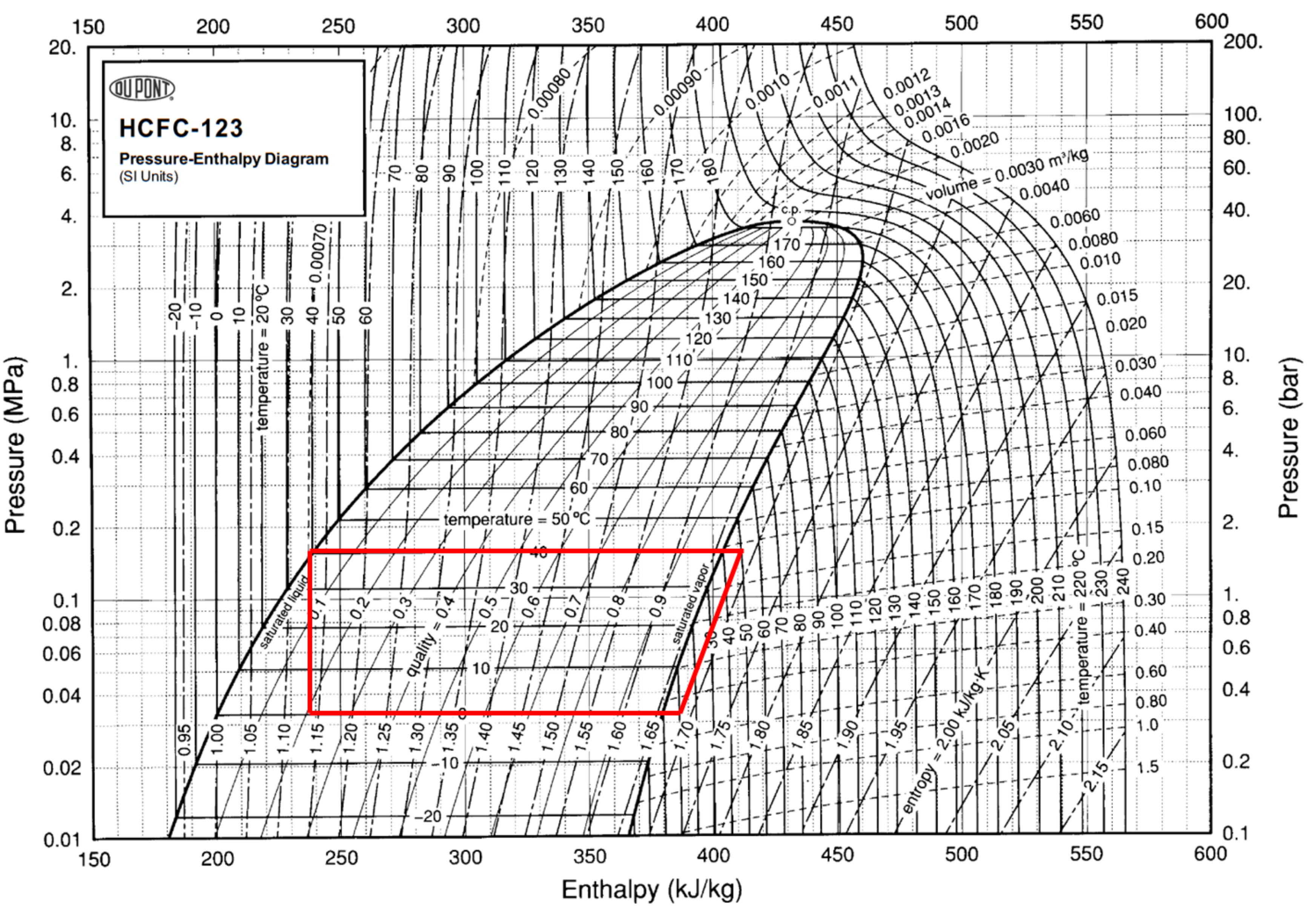
Cycle efficiency = 2.05/2.24 = 0.92 kW/RT

# Pressure – Enthalpy Diagram for HFC-134a



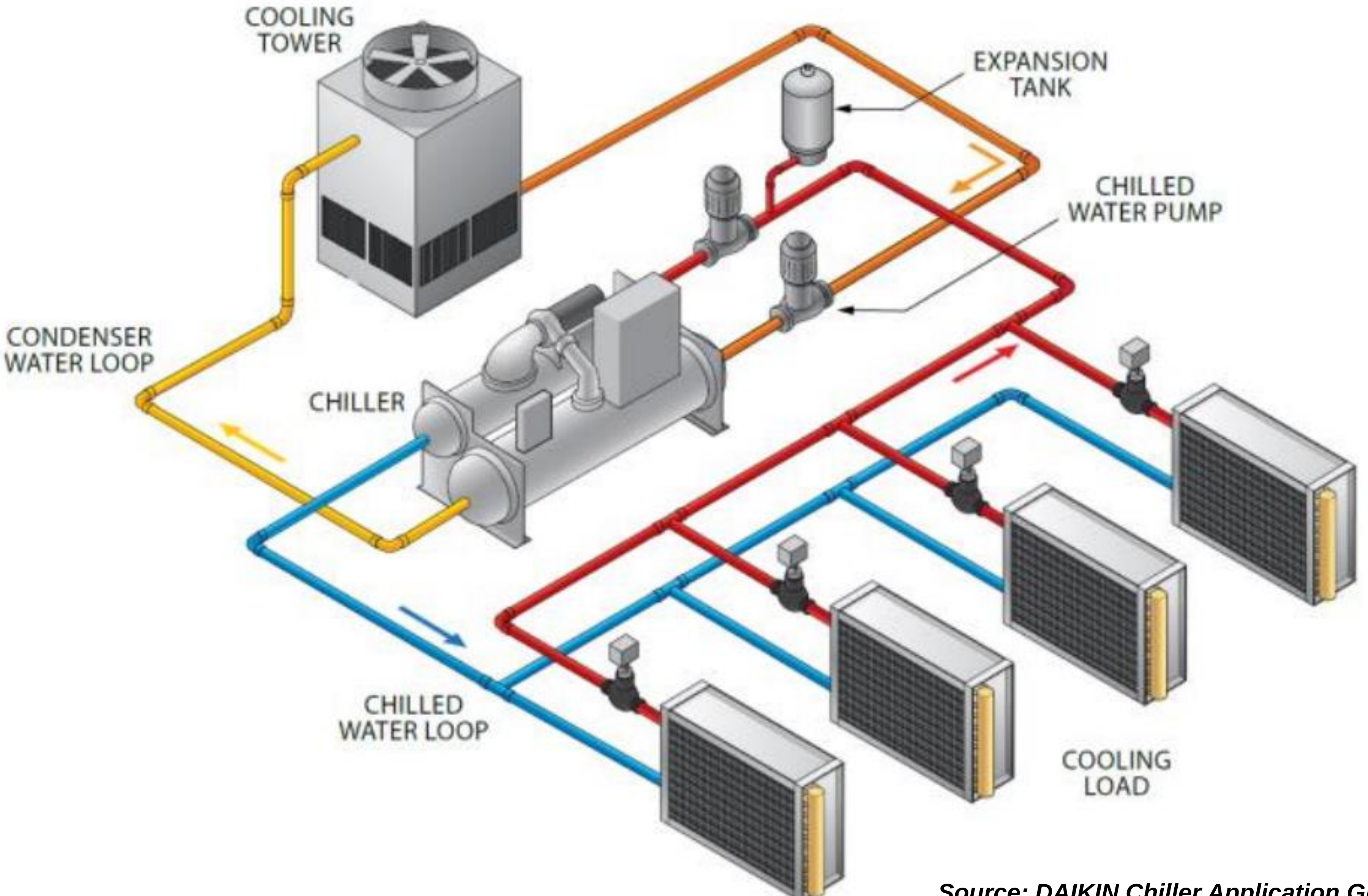
# Pressure – Enthalpy Diagram for HFC-123





# Main Components of Central Air-conditioning (Chiller) Systems

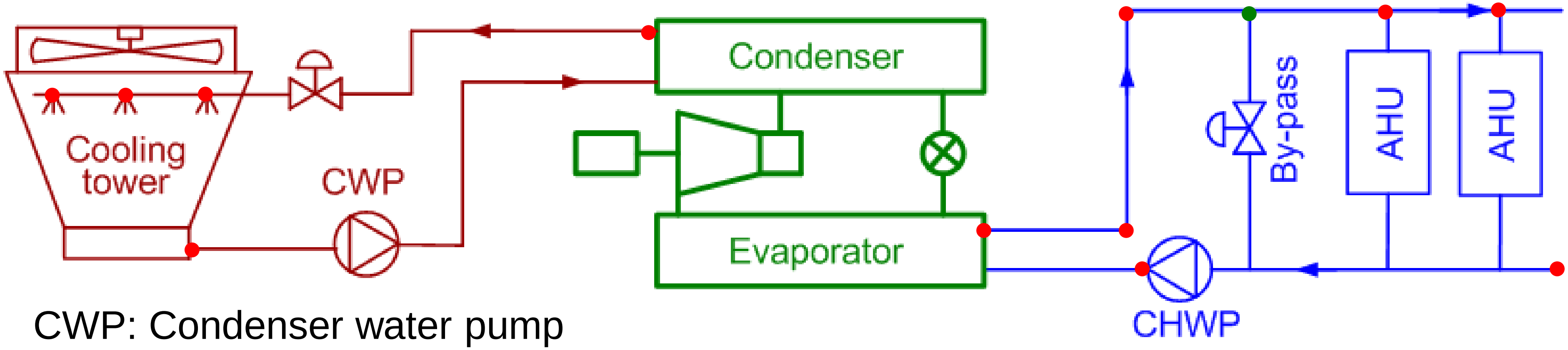




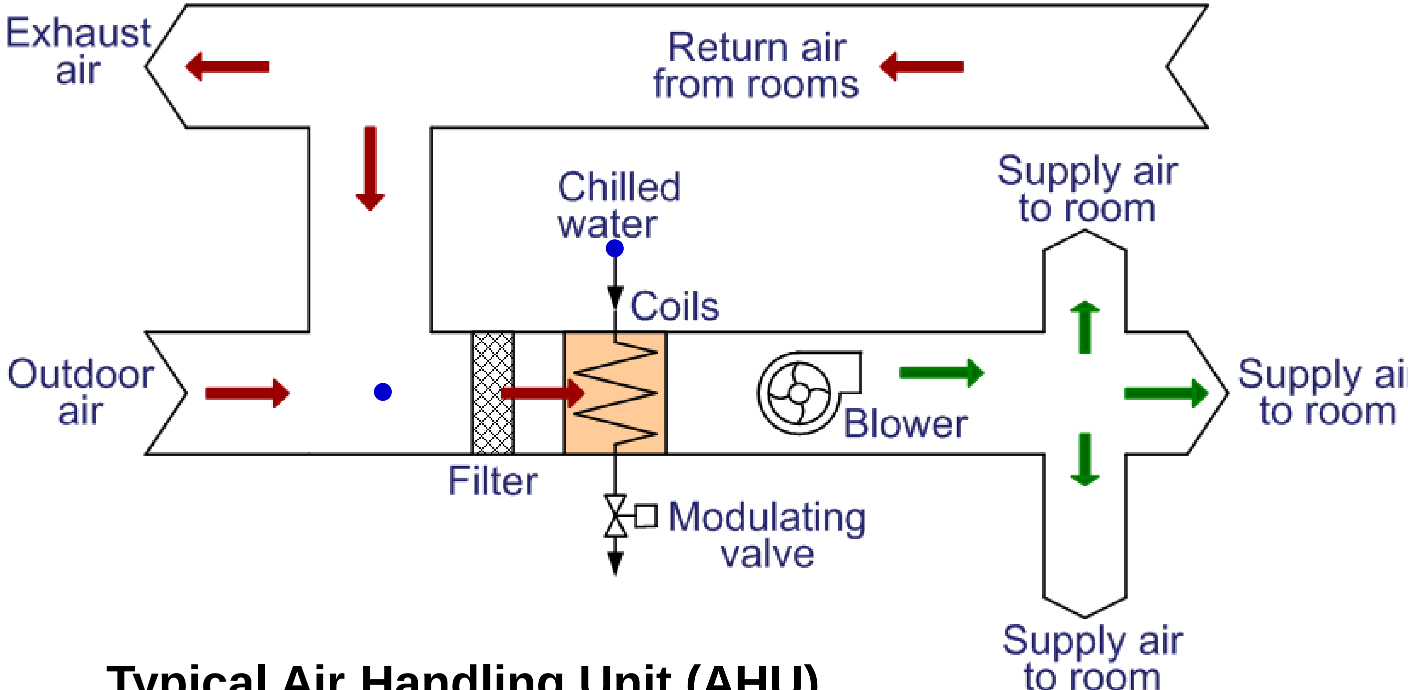

***Source: DAIKIN Chiller Application Guide***

# Main Components of Central Air-conditioning (Chiller) Systems





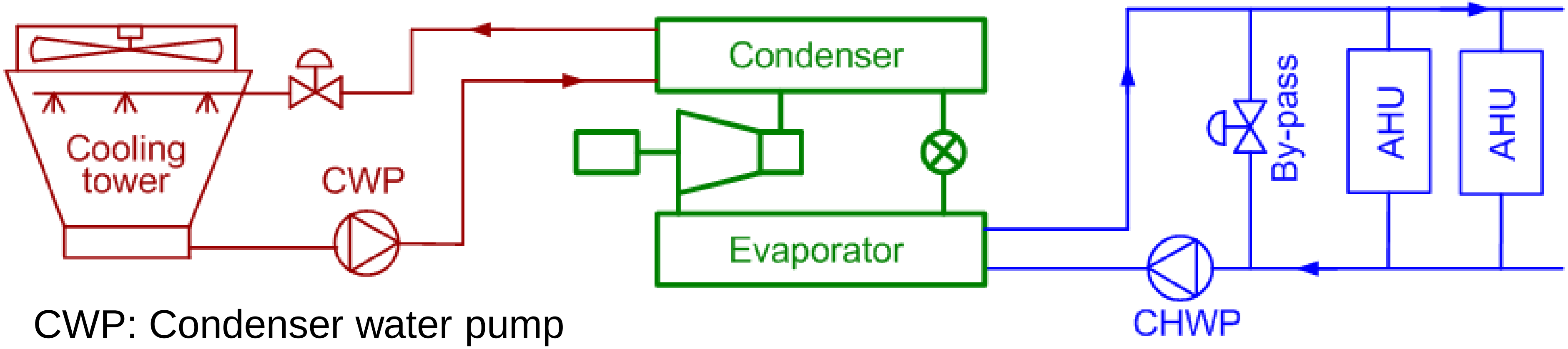

CWP: Condenser water pump
CHWP: Chilled water pump




**Typical Air Handling Unit (AHU)**

# Main Components of Central Air-conditioning (Chiller) Systems





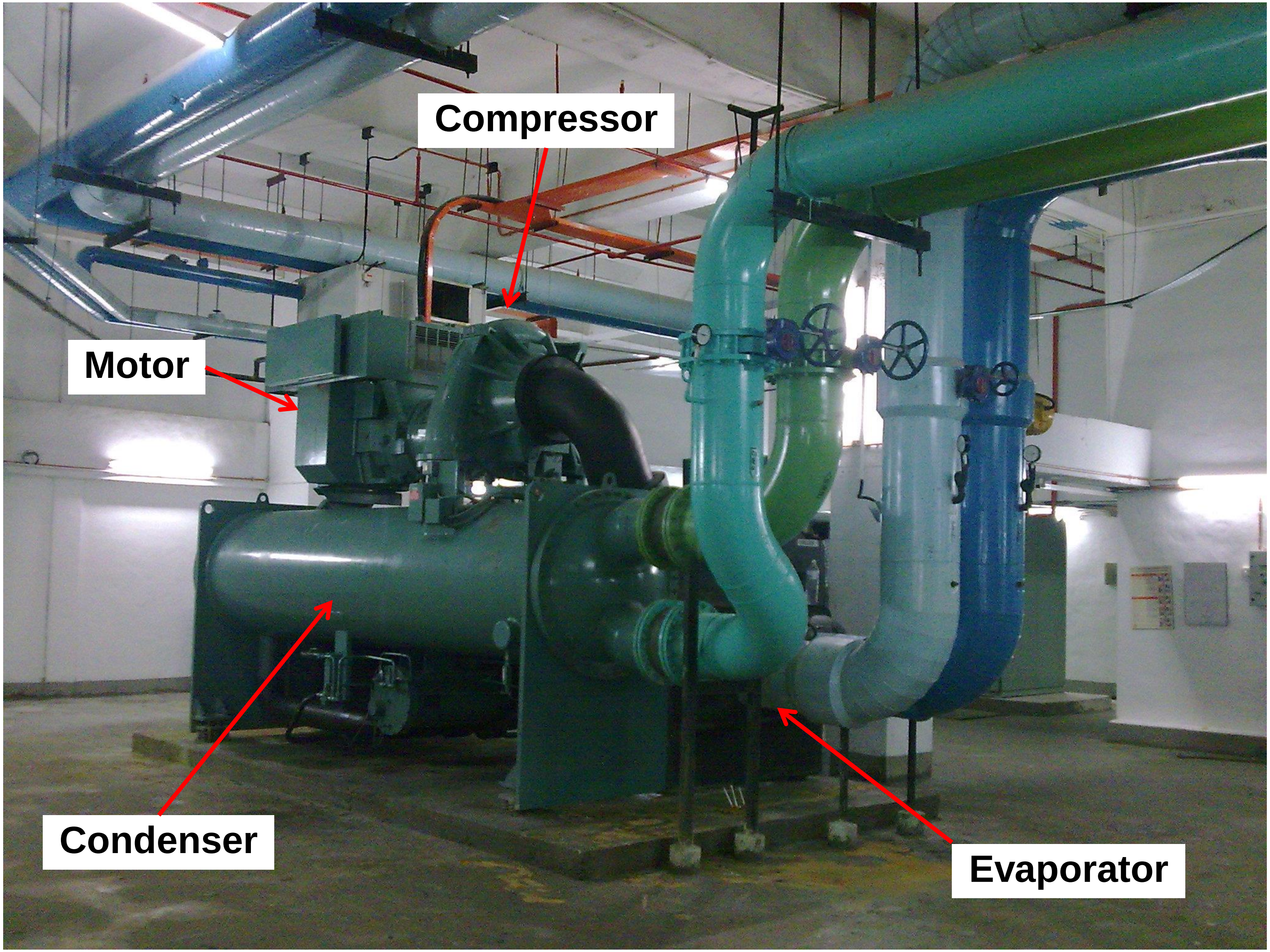

CWP: Condenser water pump
CHWP: Chilled water pump

- If CHWP is operated at constant speed, by-pass valve is partially opened to by-pass excess chilled water when chilled water demand for AHUs drops due to low cooling load

- **Energy savings opportunity:** Speed of CHWP can be modulated using Variable Speed Drive (VSD) based on real time demand of chilled water. By-pass valve will remain close until chilled water demand for AHUs drop to the minimum chilled water flow requirements for chillers. If chilled water demand for AHUs drop below minimum chilled water flow requirements for chillers, by-pass valve will be opened partially to makeup the shortfall of the chilled water for the chillers.

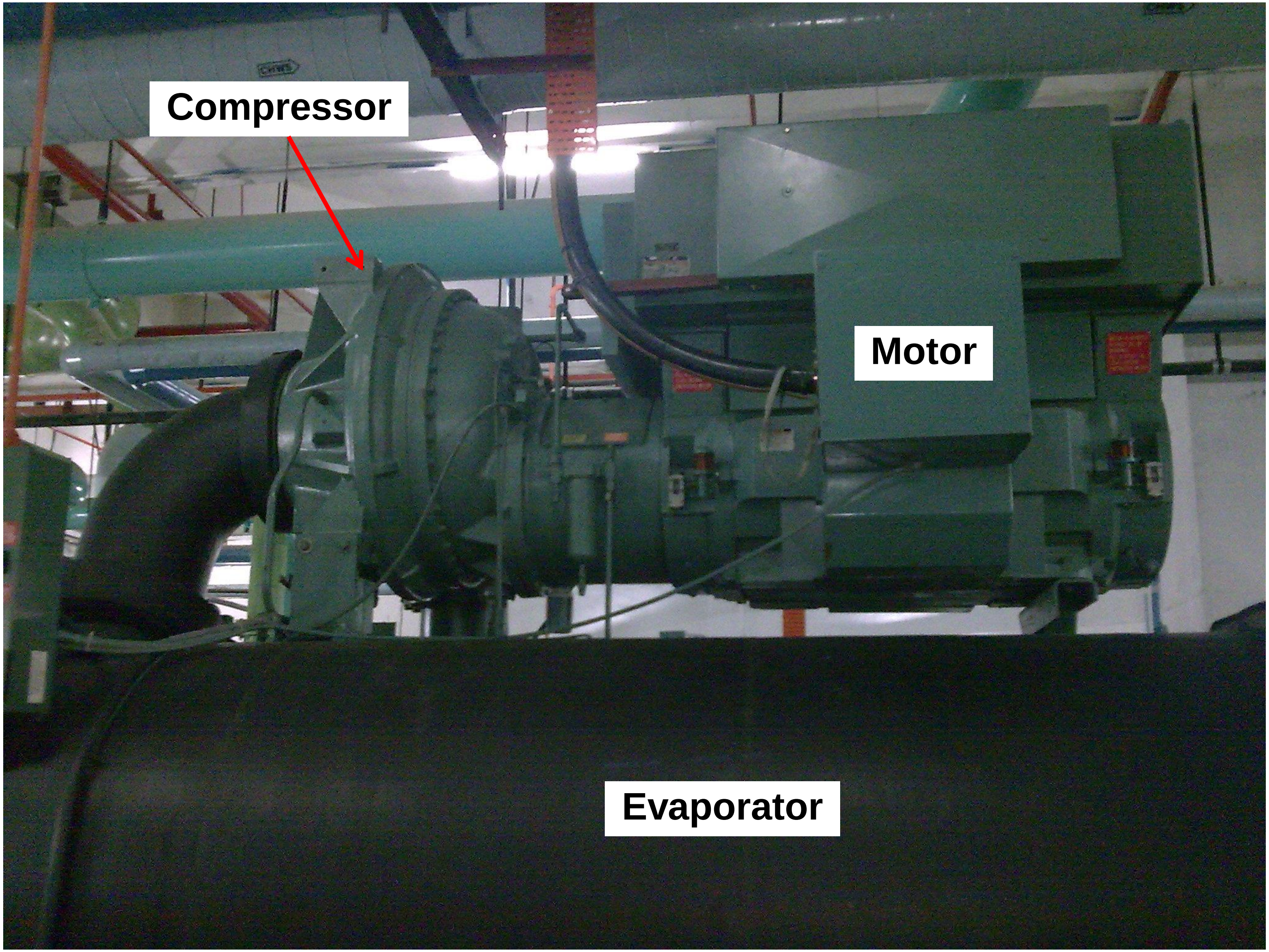
# Main Components of Central Air-conditioning (Chiller) Systems





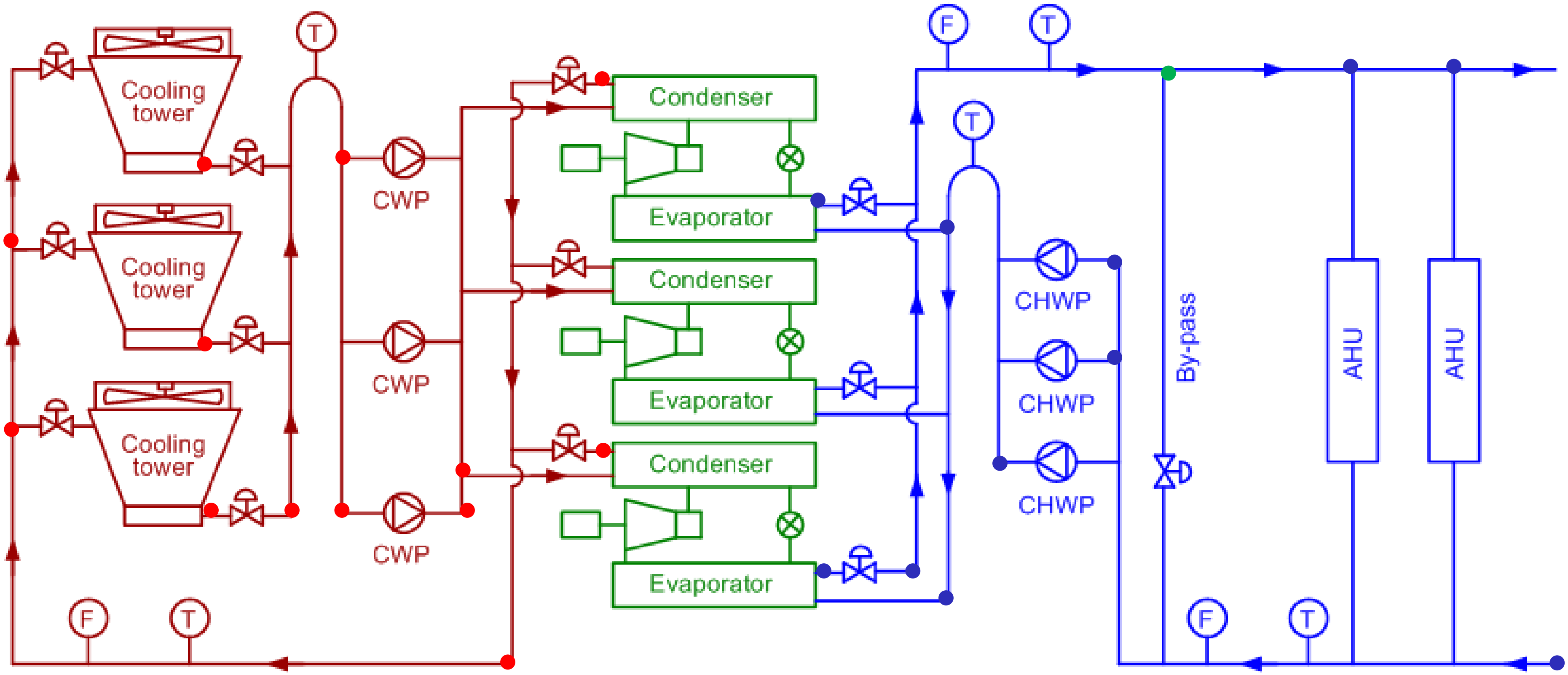
# Main Components of Central Air-conditioning (Chiller) Systems





# Primary Chilled Water Pumping System






**Primary chilled water pumping system**

CHWP: Chilled water pump

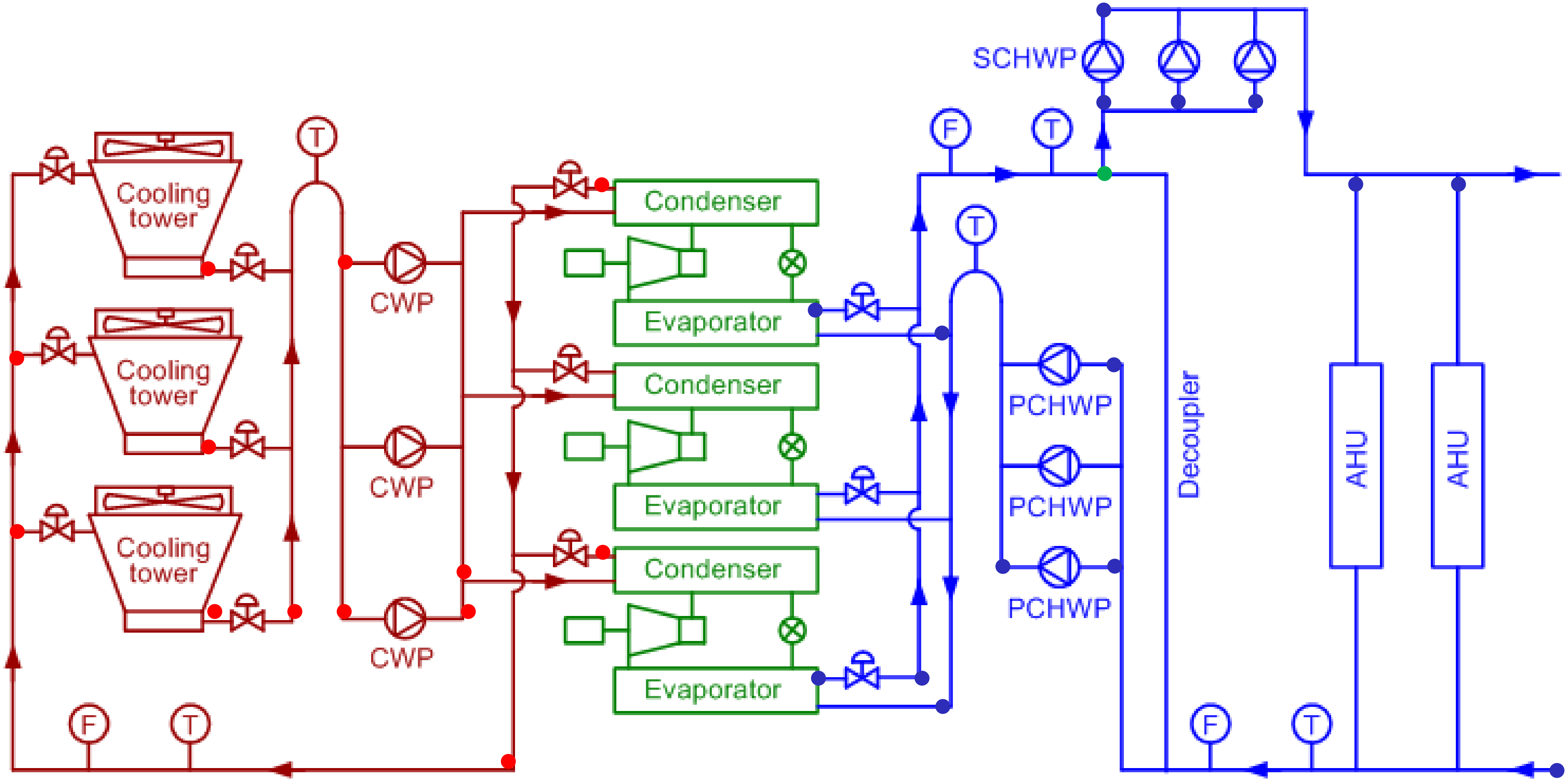
CWP: Condenser water pump

T: Temperature

F: Flow

# Primary & Secondary Chilled Water Pumping System





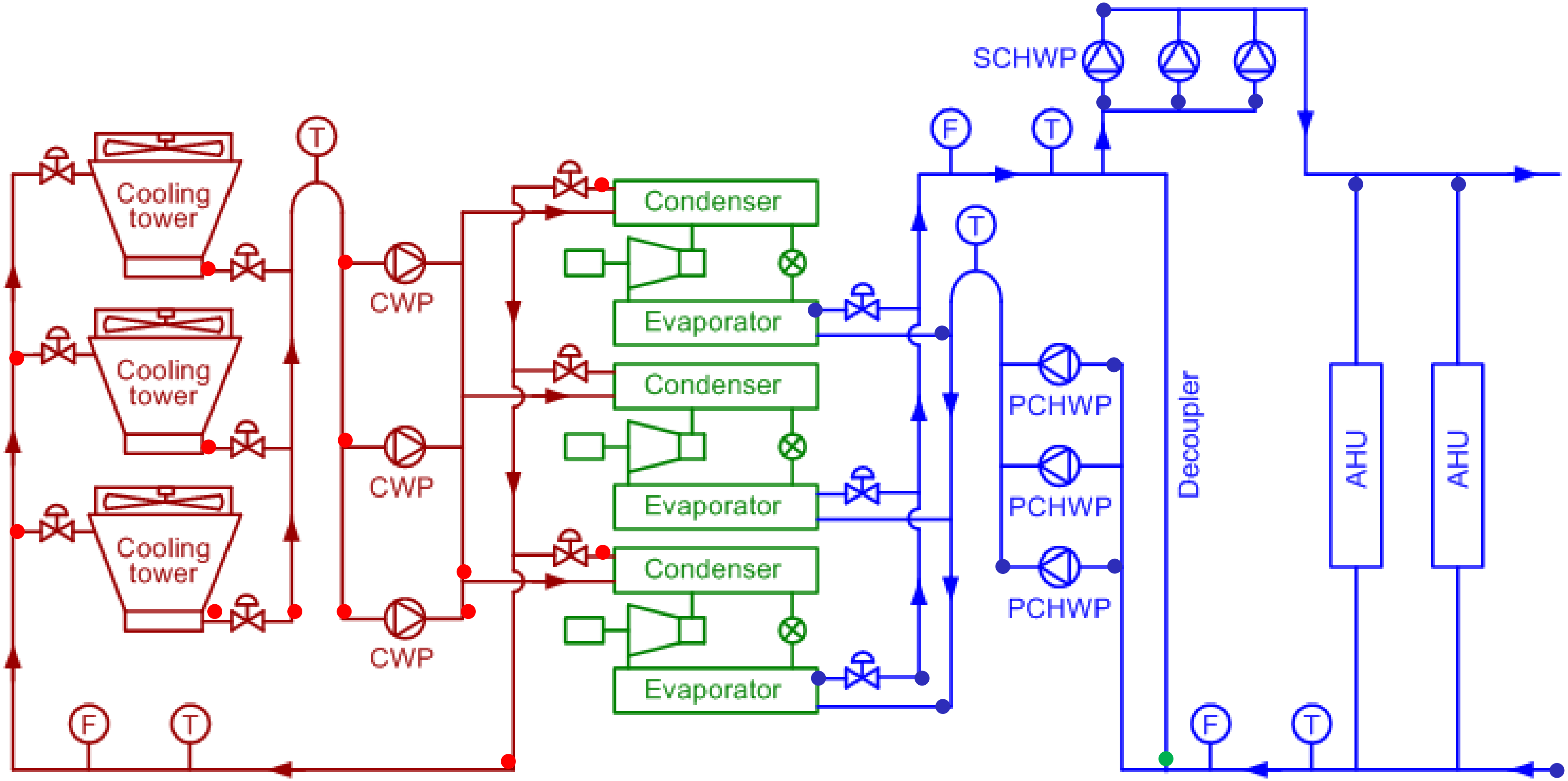

**Primary & secondary chilled water pumping system**

PCHWP: Primary chilled water pump
SCHWP: Secondary chilled water pump
CWP: Condenser water pump

T: Temperature
F: Flow

# Primary & Secondary Chilled Water Pumping System






**Primary & secondary chilled water pumping system**

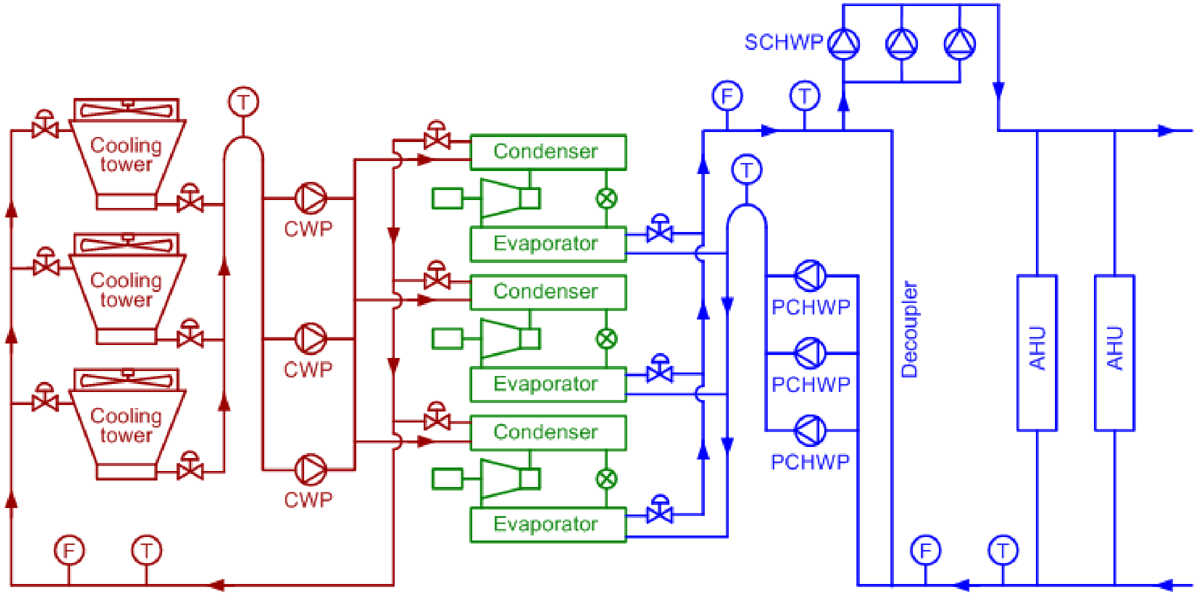
PCHWP: Primary chilled water pump
SCHWP: Secondary chilled water pump
CWP: Condenser water pump

T: Temperature
F: Flow

# Primary & Secondary Chilled Water Pumping System



- PCHWPs are usually small and operated at constant speed.
- SCHWPs are big and supply chilled water to all AHUs.



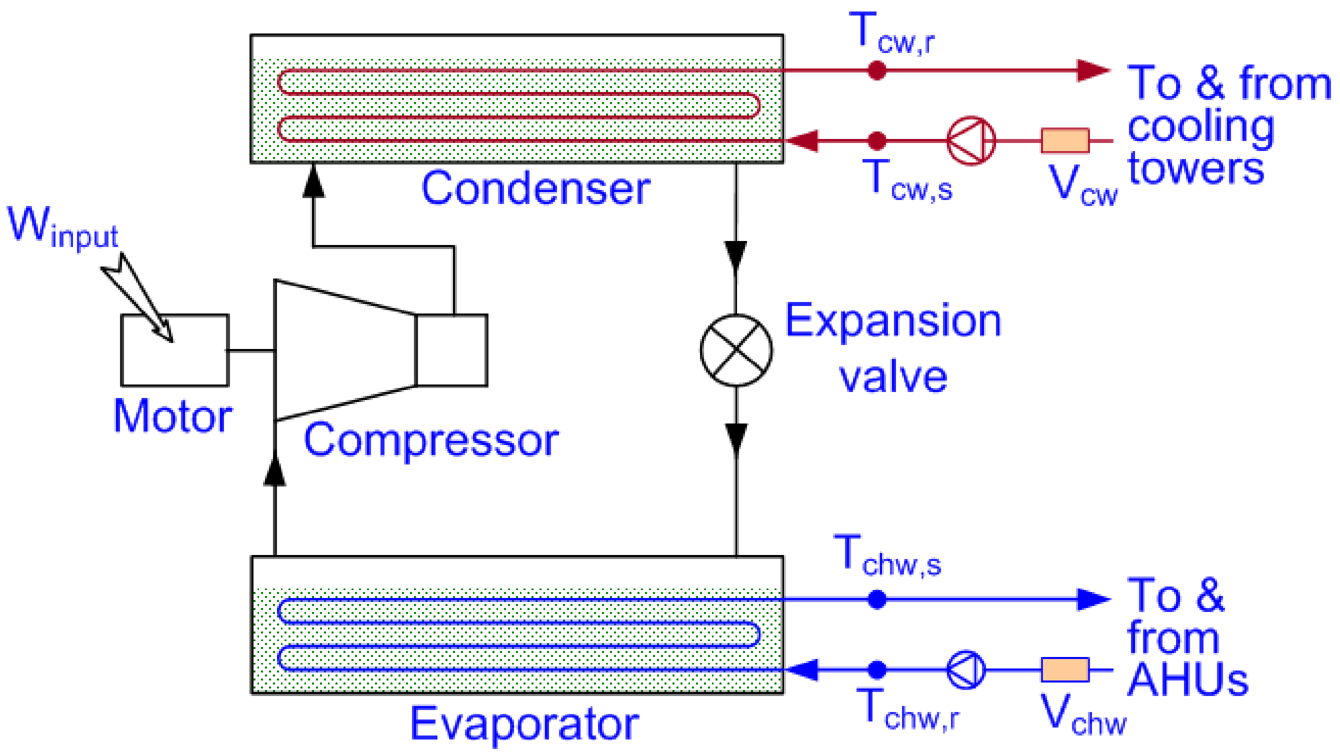

- Speed of SCHWP can be modulated using VSD based on real time demand of chilled water resulting significant pump energy savings at low part load condition.
- If PCHWP flow is higher than SCHWP flow, chilled water will flow from supply header to return header through decoupler pipe.
- If SCHWP flow is higher than PCHWP flow, chilled water will flow from return header to supply header through decoupler pipe. Then another chiller and PCHWP will be turned on.

# Operating Conditions Based on American Refrigeration Institute (ARI)



| Parameter | Value |
|---|---|
| Chilled water supply temperature | 6.7$^{o}$C (44$^{o}$F) |
| Condenser water supply temperature | 29.4$^{o}$C (85$^{o}$F) |
| Chilled water $\Delta$T at maximum load | 5.6$^{o}$C (10$^{o}$F) |
| Condenser water $\Delta$T at maximum load | 5.6$^{o}$C (10$^{o}$F) |
| Chilled water flow rate | 2.4 usgpm/RT (0.15 l/s per RT) |
| Condenser water flow rate | 3 usgpm/RT (0.19 l/s per RT) |

# Calculation of Chiller Cooling Load




$V_{chw}$ = chilled water flow rate, $m^3/s$

$\rho_{chw}$ = chilled water density, 1000 $kg/m^3$

$C_p$ = sp. heat of chilled water, 4.2 kJ/kg. K

$T_{chw,r}$ = chilled water return temp, $^oC$

$T_{chw,s}$ = chilled water supply temp, $^oC$

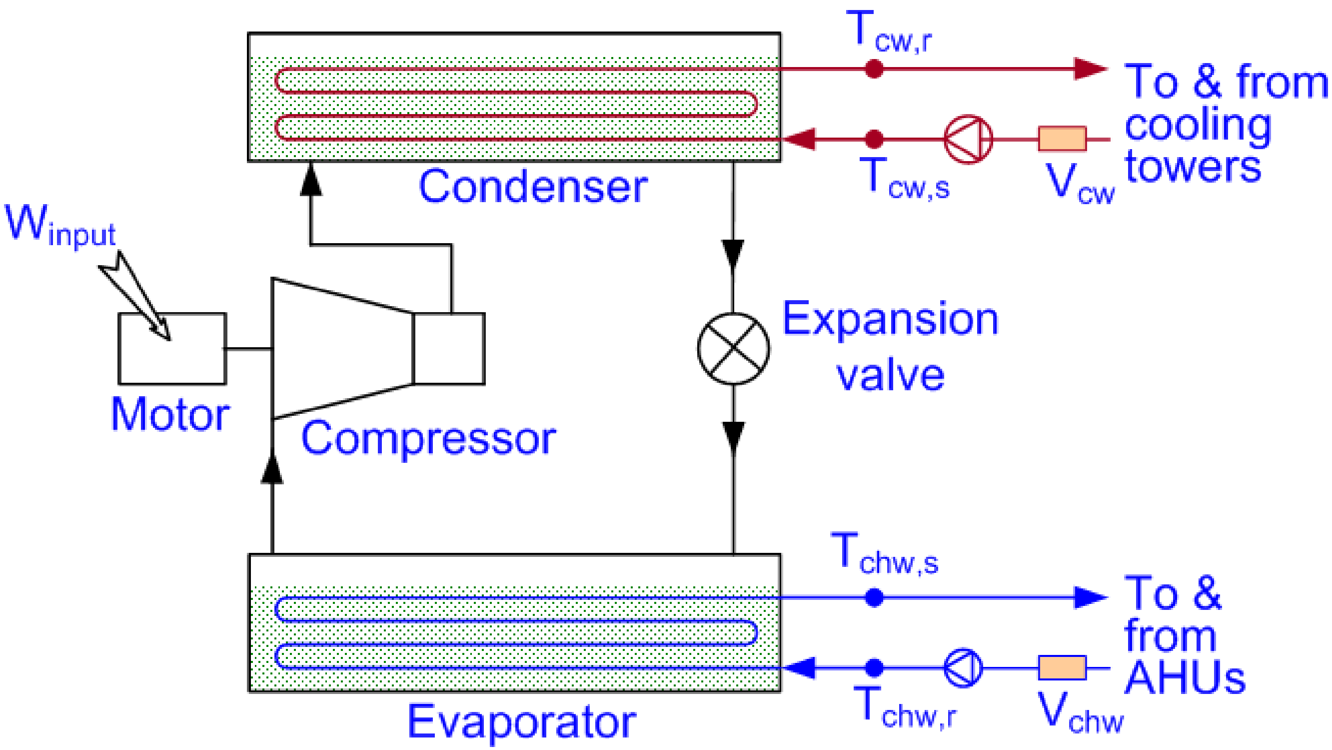
Cooling load or Heat gain in evaporator, kW: $Q_{ev} = V_{chw}\rho_{chw}C_p(T_{chw,r}-T_{chw,s})$

Cooling load or Heat gain in evaporator, RT

= (Heat gain in evaporator, kW) / 3.517

# Calculation of Heat Rejection by Condenser






$V_{cw}$ = condenser water flow rate, $m^3/s$

$\rho_{cw}$ = condenser water density, 1000 $kg/m^3$

$C_p$ = sp. heat of condenser water, 4.2 kJ/kg. K

$T_{cw,r}$ = condenser water return temp, $^oC$

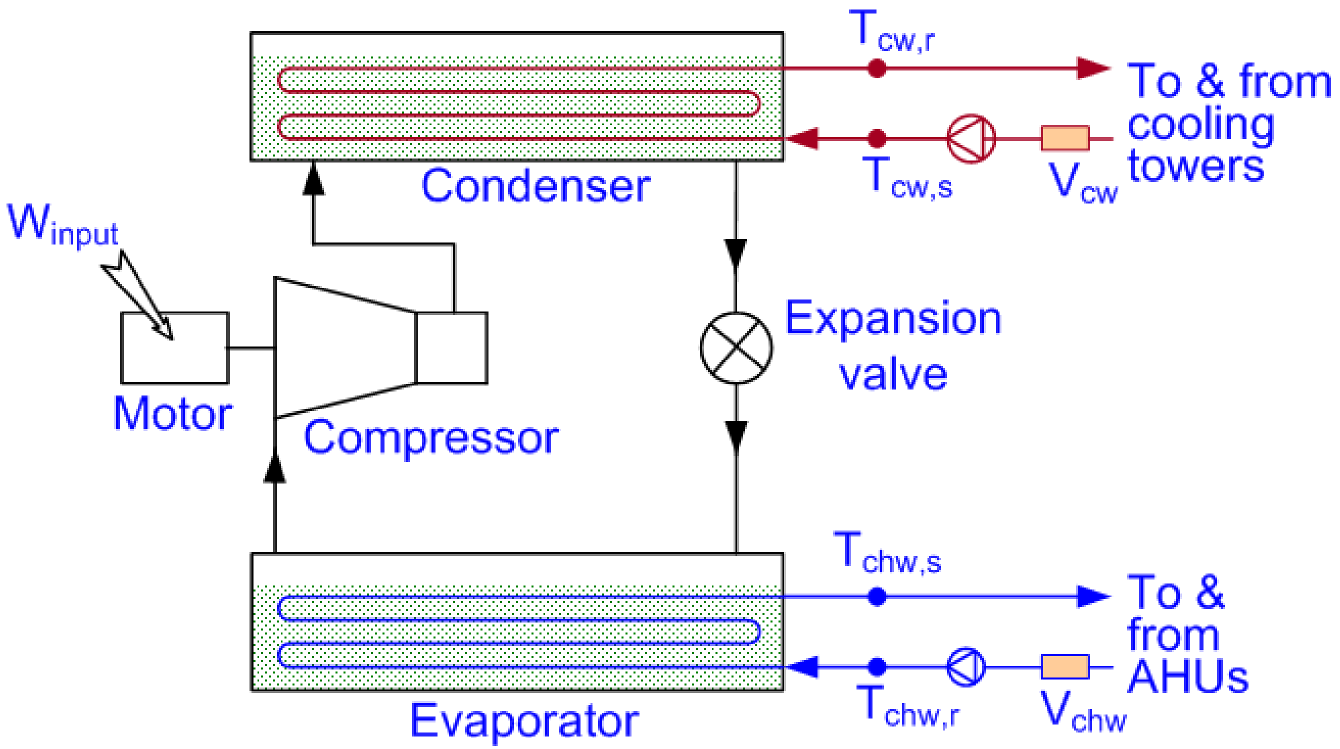
$T_{cw,s}$ = condenser water supply temp, $^oC$

Heat rejection by condenser, kW: $Q_{cd} = V_{cw}\rho_{cw}C_p(T_{cw,r}-T_{cw,s})$

Heat rejection by condenser, RT

= (Heat rejection by condenser, kW) / 3.517

# Chiller Energy Balance Equation




Heat losses or heat gain caused by radiation, convection, bearing friction, oil coolers, etc. are relatively small and may or may not be considered in overall heat balance.

- Omitting the effect of the above heat losses and gains, general overall heat balance equation can be written as:

$$Q_{ev} + W_{input} = Q_{cd}$$

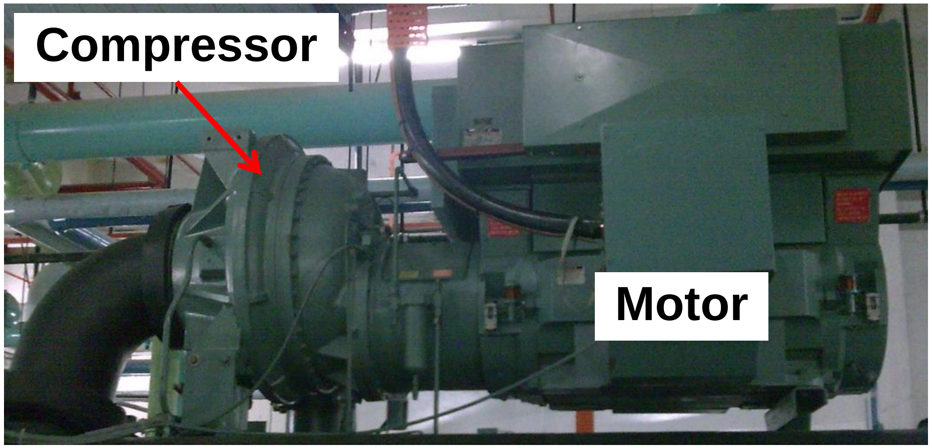
Where $Q_{ev}$ = heat gain in evaporator, kW

$W_{input}$ = electrical power input to compressor shaft, kW

$Q_{cd}$ = heat rejected by condenser, kW

# Motor and Compressor Coupling

- **Open-type compressor with prime mover and external gear drive**



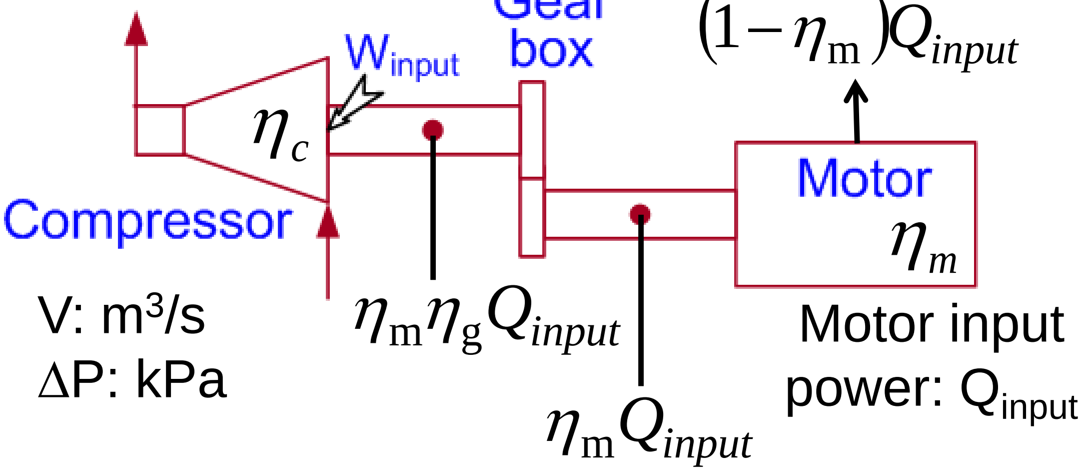

Compressor output power = $V\Delta P$ kW

$$= \eta_c \eta_g \eta_m Q_{input}$$

Compressor input power, $W_{input}$

$$= \eta_g \eta_m Q_{input}$$

Output power
= $V\Delta P$ kW




$$W_{input} = Q_{prime\ mover} - Q_{gear}$$

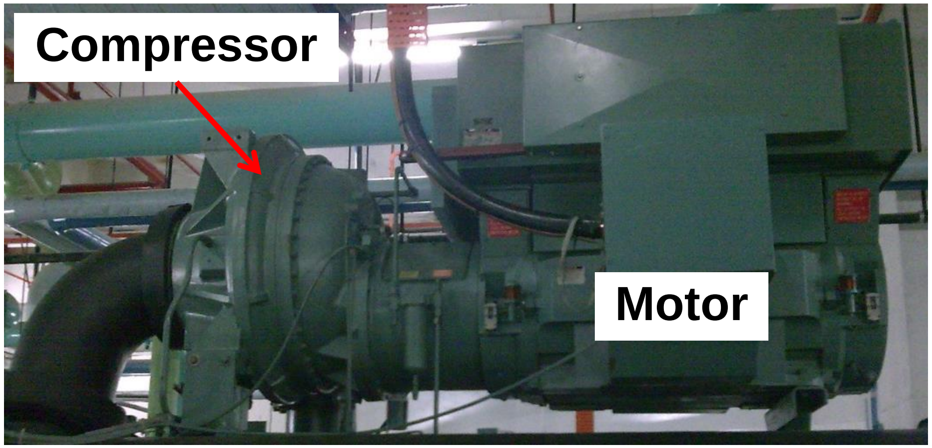
$W_{input}$ = Electrical power input to compressor shaft, kW

$Q_{prime\ mover}$ = Power delivered by prime mover or motor, kW

$Q_{gear}$ = Friction loss in gear box, kW

# Motor and Compressor Coupling

- **Open-type compressor with direct drive:**




Compressor input power, $W_{input}$

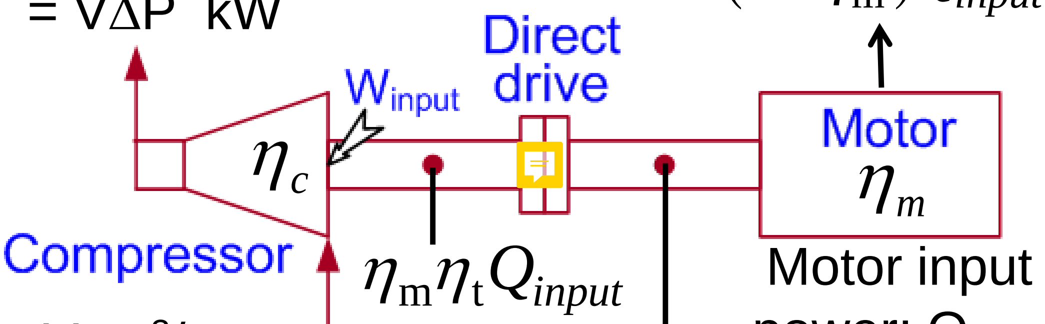
$$= \eta_t \eta_m Q_{input}$$

$W_{input}$ = electrical power input to compressor shaft, kW

= electrical power input to motor x (motor efficiency x transmission efficiency)

Output power = $V\Delta P$ kW

$(1-\eta_m)Q_{input}$




$\eta_m \eta_t Q_{input}$

Motor input power: $Q_{input}$

$\eta_m Q_{input}$

V: $m^3/s$

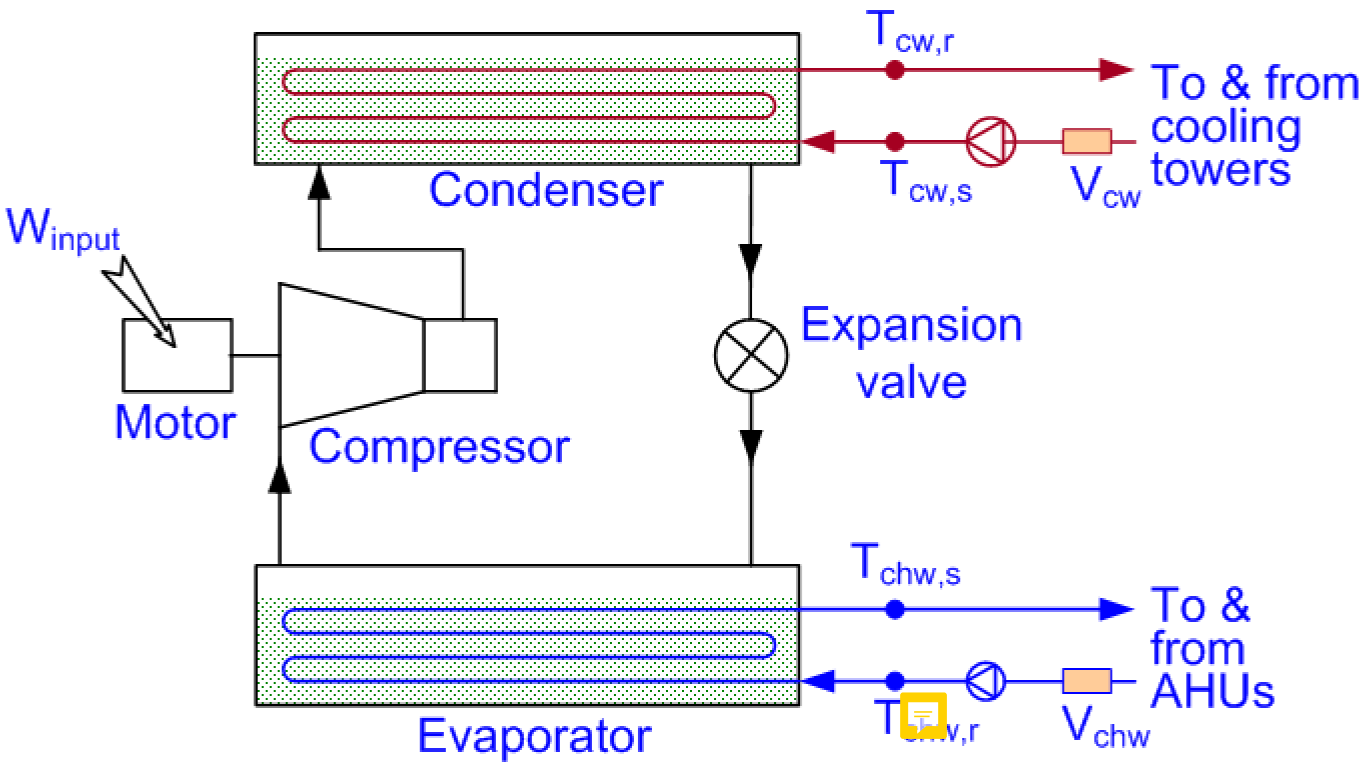
$\Delta P$: kPa

- **For hermetic package, where motor is cooled by refrigerant:**

$W_{input}$ = electrical power input to the motor of compressor, kW

# Chiller Overall Heat Balance Calculation for Measured Data Verification






**% unbalanced heat:** $$\frac{\left(Q_{ev} + W_{input}\right) - Q_{cd}}{Q_{cd}} \text{x}100$$

**BCA requirements:** Unbalanced heat is less than 5% for minimum 80% of measured data

# Determination of Chiller Efficiency



- Chiller efficiency is defined as electric power consumed by the motor of compressor to produce one unit of cooling effect

- Chiller efficiency = Electric power consumed by motor of compressor / Cooling produced

- Chiller efficiency in kW/RT = Electric power consumed by motor of compressor in kW / Cooling produced in RT

- Coefficient of Performance, COP = Cooling produced in kW / Electric power consumed by motor of compressor in kW

- (kW refrigeration effect = RT x 3.517)

- Input electrical power to the motor of compressor can be measured using power meter

- Cooling produced can be calculated using measured chilled water flow rate, supply and return temperature

# Determination of Chiller Plant System Efficiency



$$\text{System CoolingLoad, RT} = \sum \text{IndividualChiller CoolingLoad, RT}$$

Chiller Plant System Efficiency

$$= \frac{\sum power\ of\ \ Individual\ \ Chiller, CHWPP, CHWSP, CWP\ \&\ CT\ electrical\ load, kW}{System\ Cooling\ \ Load, RT}$$

<u>Where</u>

| | |
|---|---|
| CHWPP | Chilled Water Primary Pump |
| CHWSP | Chilled Water Secondary Pump |
| CT | Cooling Tower |
| CWP | Condenser Water Pump |

- If chilled water tertiary pump is used, power consumption of tertiary pump to be included in Chiller Plant System Efficiency calculation
- AHU fan power is not included in Chiller Plant System Efficiency calculation

For axial fan cooling tower (based on SS 530):

1 kW fan power can cool 3.23L/s water from 35ºC to 29ºC

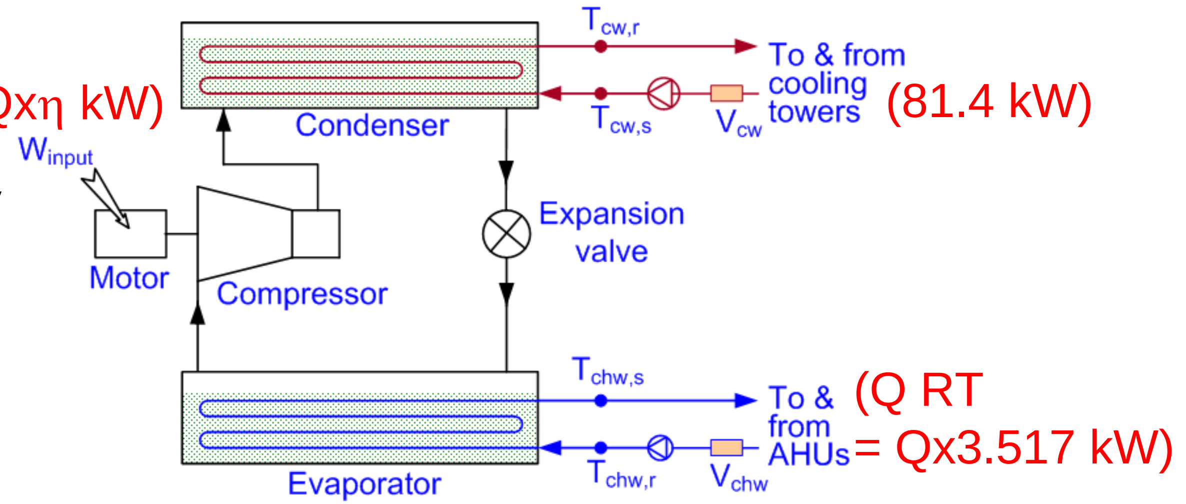
$$= 3.23\frac{L}{s} \times \frac{1m^3}{1000L} \times \frac{1000kg}{m^3} \times 4.2\frac{kJ}{kgK} \times (35-29)K = 81.4\,kW_{total}$$

Let, Cooling load of a chiller = Q RT = Qx3.517 kW

If efficiency of the chiller is $\eta$ = 0.577 kW/RT

Therefore, input electric power to the compressor of chiller = Qx$\eta$ kW

Energy balance of chiller: (Qx$\eta$ kW)




Input energy = output energy

Qx3.517 + Qx$\eta$ = 81.4

Or, Q = 20 RT

Therefore, energy efficiency cooling tower fan = (1 kW)/(20 RT) = 0.05 kW/RT

# Cooling Tower Fan Power



- Power meter can be used to measure cooling tower fan power consumption

- Cooling tower fan power consumption can be less than the rated value due to the use of VSD or loosening of belt

- If chiller cooling produced (RT) is known, Cooling tower fan power consumption, kW/RT = (Cooling tower measured fan power, kW) / (Chiller produced, RT)

# SS 553: Chilled Water Pump Requirement

SS 553: Chilled water pump power = 349 kW/($m^3$/s)

$$= 349 \frac{kW}{m^3/s} \; x \frac{1\, m^3/s}{1000\, L/s} \; x \frac{0.0631\, L/s}{1\, gpm} \; x \frac{2.4\, gpm}{1\, RT}$$ = 0.0529 kW/RT

- Motor exceeding 15 kW should have controls and/or devices (such as VSD) that will result in motor power no more than 30% of design wattage at 50% of design flow rate
- Power meter can be used to measure directly the power consumption of motor of chilled water pump
- If VSD is used to modulate chilled water flow based on demand, chilled water pump power consumption can be less than the rated value
- If chiller cooling load (RT) is known, chilled water pump power consumption, kW/RT = (Input power to motor of chilled water pump, kW) / (Chiller cooling load, RT)

# SS 553: Condenser Water Pump Requirement



SS 553: Condenser water pump power = 301 kW/(m$^3$/s)

$$= 301 \frac{kW}{m^3/s} \, x \, \frac{1\, m^3/s}{1000\, L/s} \, x \, \frac{0.0631\, L/s}{1\, gpm} \, x \, \frac{3.0\, gpm}{1\, RT} = 0.0569 \text{ kW/RT}$$

- Motor exceeding 15 kW should have controls and/or devices (such as VSD) that will result in motor power no more than 30% of design wattage at 50% of design flow rate

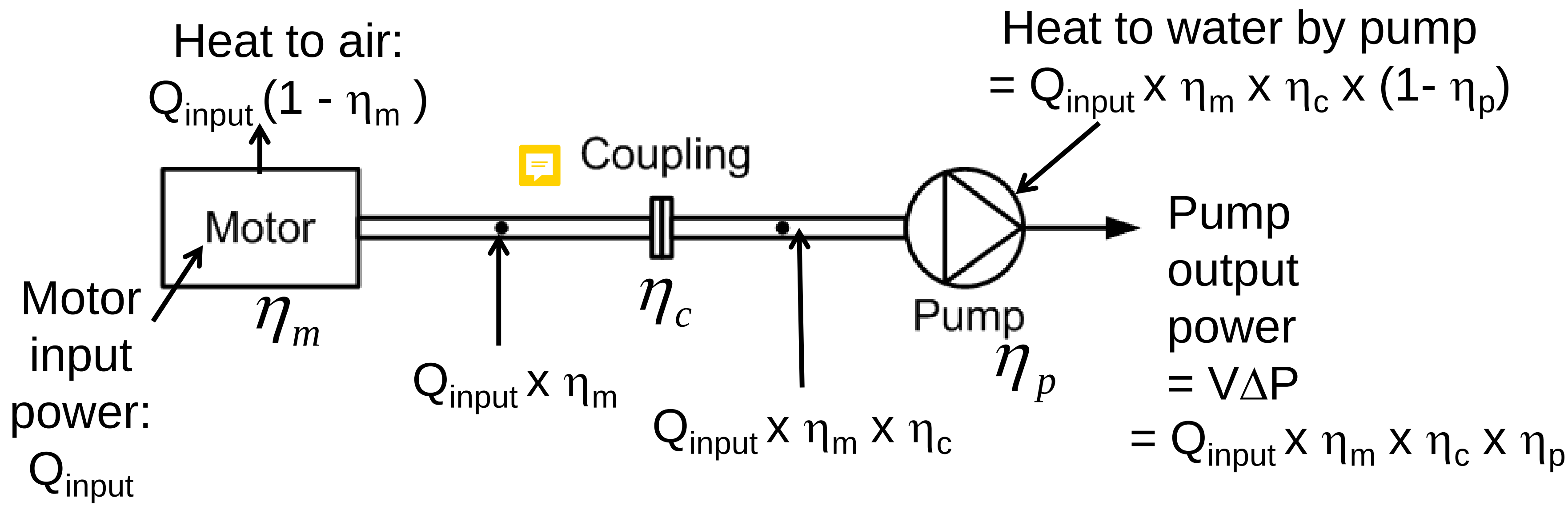
- Power meter can be used to measure directly the power consumption of motor of condenser water pump

- If VSD is used to modulate condenser water flow based on demand, condenser water pump power consumption can be less than the rated value

- If chiller cooling load (RT) is known, condenser water pump power consumption, kW/RT = (Input power to motor of condenser water pump, kW) / (Chiller cooling load, RT)

# Heat Input to Water by Pumps






Let,

$T_{in}$ = temperature of water at inlet of pump

$T_{out}$ = temperature of water at the outlet of pump

Heat added by pump to water = $V\rho C_p (T_{out} - T_{in})$

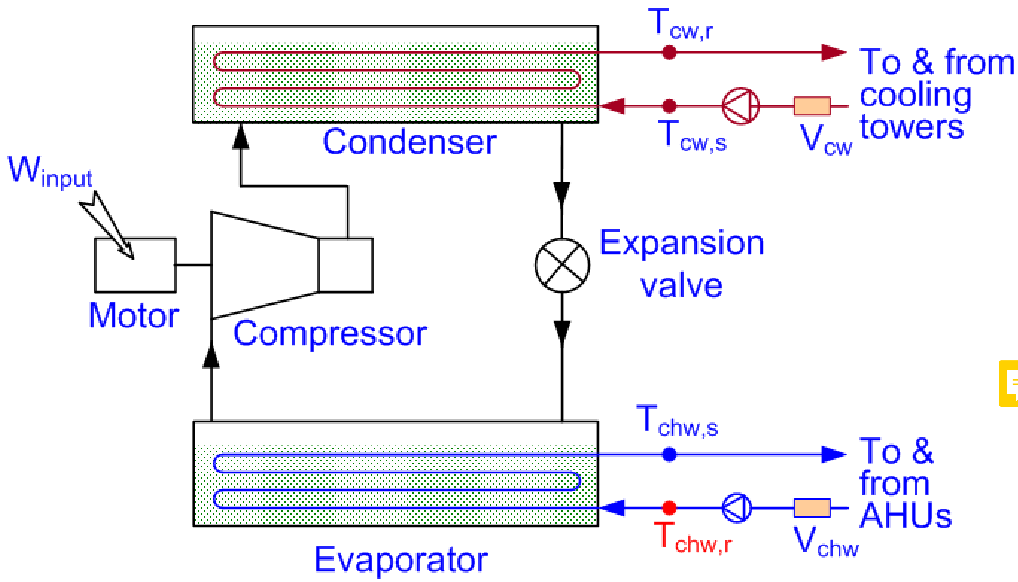
$$Q_{input} \times \eta_m \times \eta_c \times (1 - \eta_p) = V\rho C_p (T_{out} - T_{in})$$

Calculate $T_{out}$

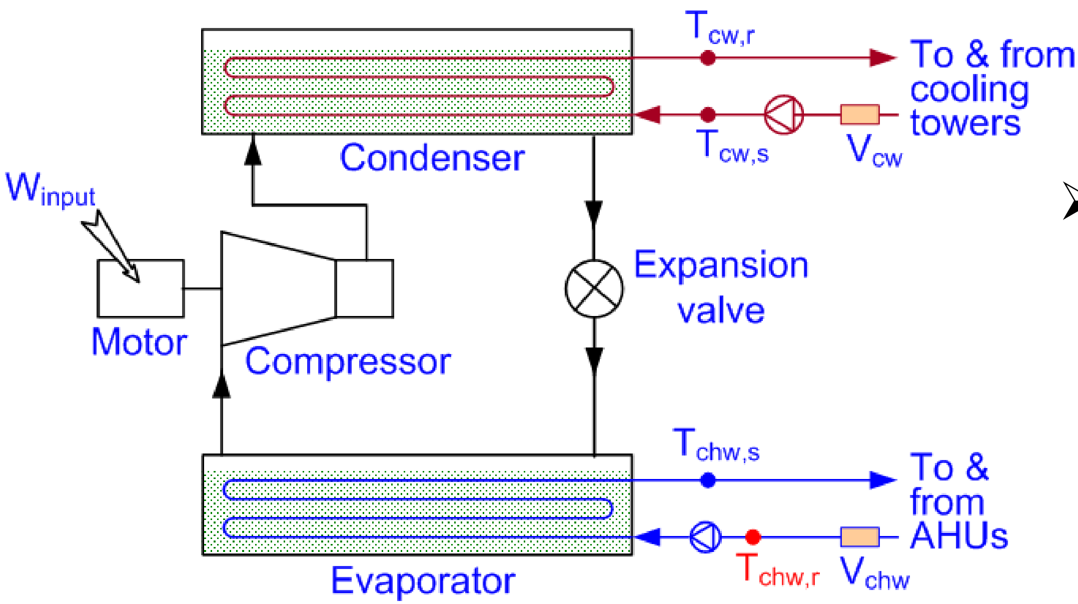
- For energy balance calculation, location of temperate sensors should be considered carefully and make necessary correction of temperatures

# Locations of Temperature Sensors



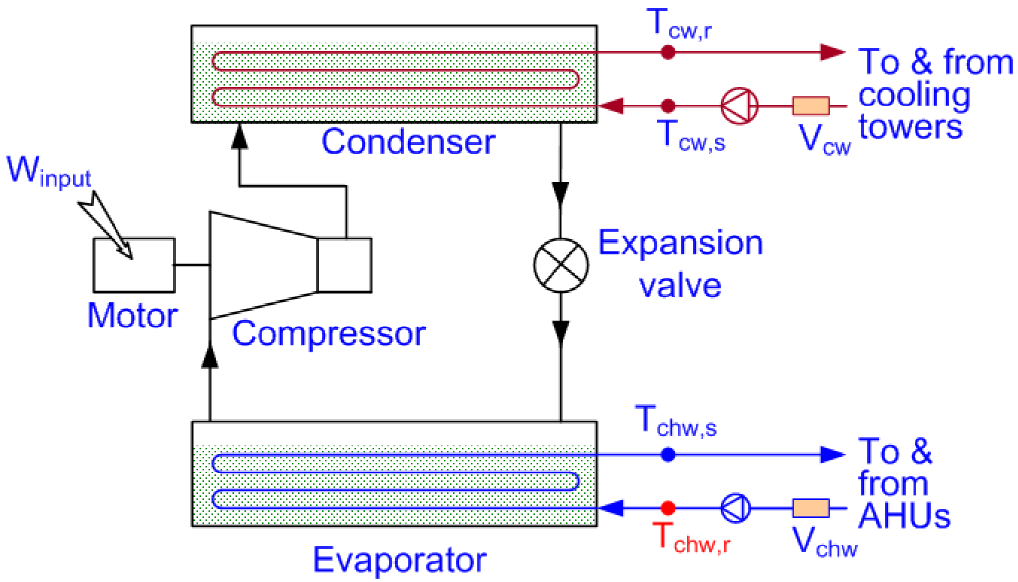



- Chilled water return temperature sensor located **after** chilled water pump

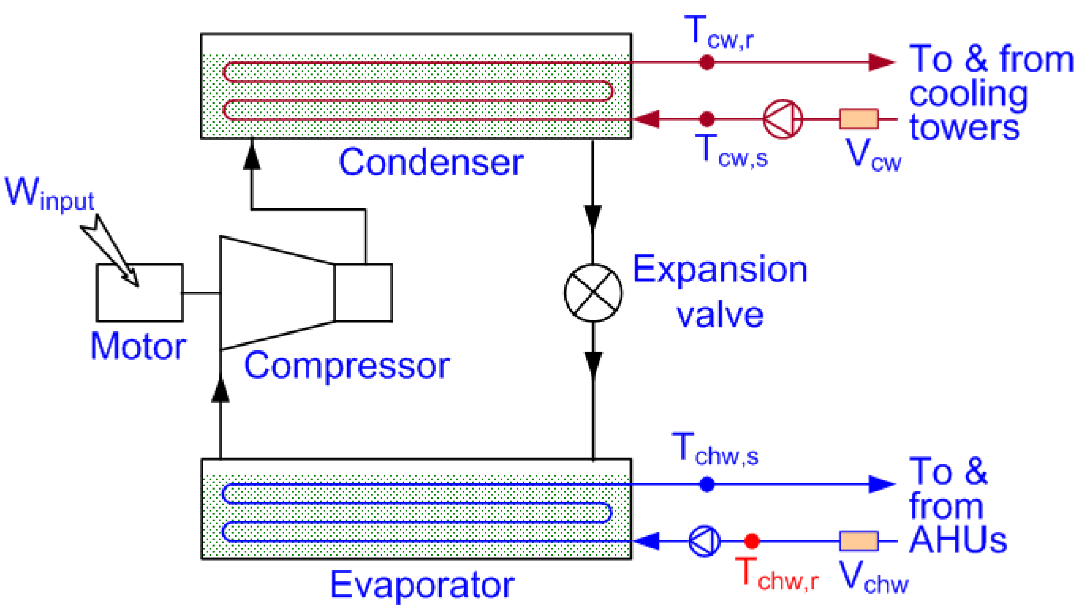



- Chilled water return temperature sensor located **before** chilled water pump

# Locations of Temperature Sensors




- Condenser water supply temperature sensor located **after** condenser water pump




Condenser water supply temperature sensor located **before** condenser water pump

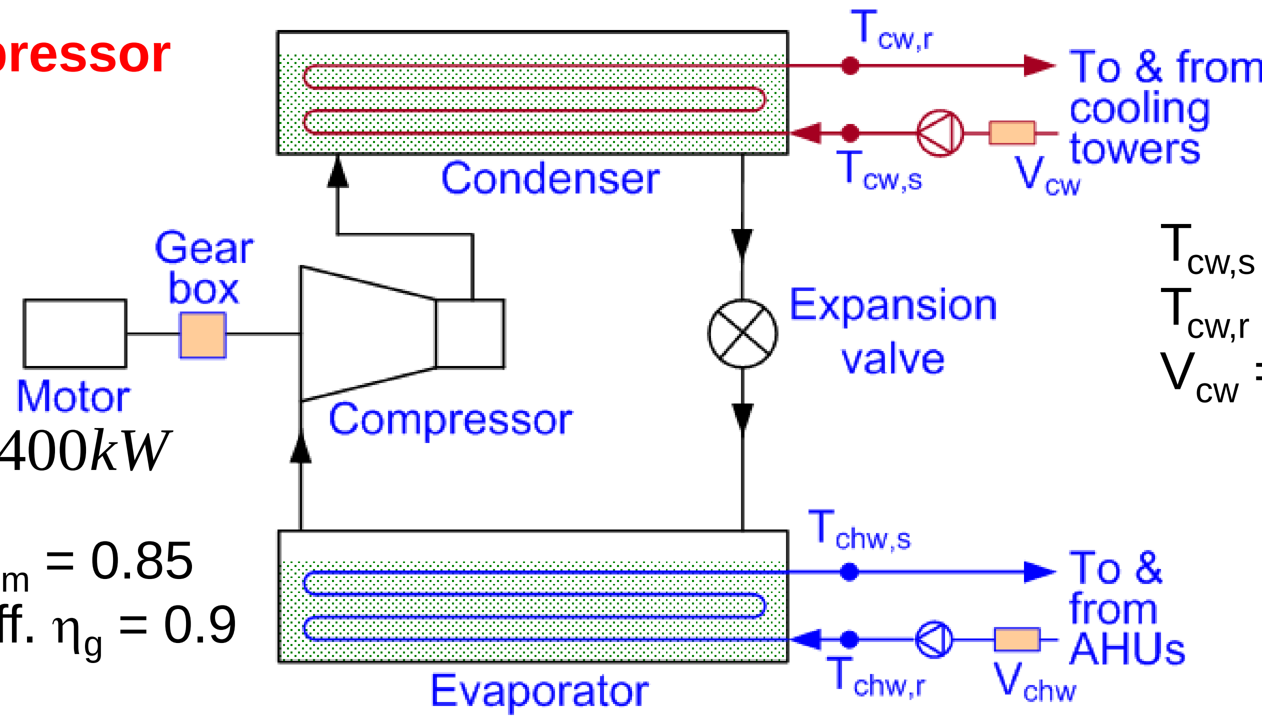
# Minimum System Efficiency Requirement for >300RT Water Cooled Centrifugal Chiller



| Description | SS reference | kW/RT |
|---|---|---|
| Water Cooled Centrifugal Chiller (>300RT) | SS530 | 0.577 |
| Chilled water pumps | SS553 | 0.0529 |
| Condenser water pumps | SS553 | 0.0569 |
| Cooling towers | SS530 | 0.05 |
| **System efficiency** | | **0.7368** |

# Problem

**Open compressor**




$T_{cw,s} = 30^oC$

$T_{cw,r} = 35^oC$

$V_{cw} = 0.1262\ m^3/s$

$$W_{m,input} = 400kW$$

Motor eff. $\eta_m = 0.85$

Gear box eff. $\eta_g = 0.9$

$Q_{eva} = ?$

$\eta_{chiller} = ?$

**Solution:** Power input to compressor $W_{c,in} = W_{m,input} \times \eta_m \times \eta_g = 306$ kW

Condenser heat rejection $Q_{condenser} = V_{cw}\ \rho_w\ C_{p,w}\ (T_{cw,r} - T_{cw,s})$

$= 0.1262 \times 1000 \times 4.2\ (35\text{-}30) = 2650$ kW

Energy balance for chiller: $Q_{eva} + W_{c,in} = Q_{condenser}$

$Q_{eva} = 2344$ kW $= 2344/3.517 = 666.4$ RT

Chiller eff. $\eta_{chiller} = W_{m,input}/Q_{eva}$

$\eta_{chiller} = 0.6$ kW/RT

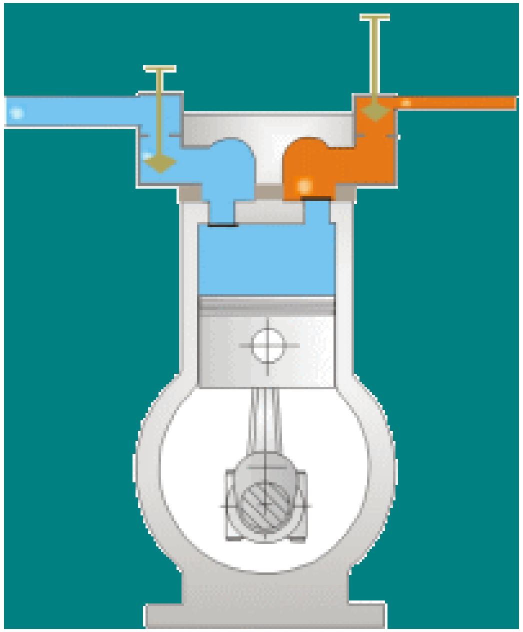
# Common Types of Compressor for Different Capacity Chillers



- Reciprocating (below 100RT)
- Scroll (100 to 1000RT)
- Screw (up to about 600RT)
- Centrifugal (100RT to upper limit)
- Absorption (50RT to upper limit)

# Chillers with Reciprocating Compressor





# Chiller with Scroll Compressor

a) Refrigerant enters the outer openings

b) Open passages are sealed off as refrigerant is drawn in.

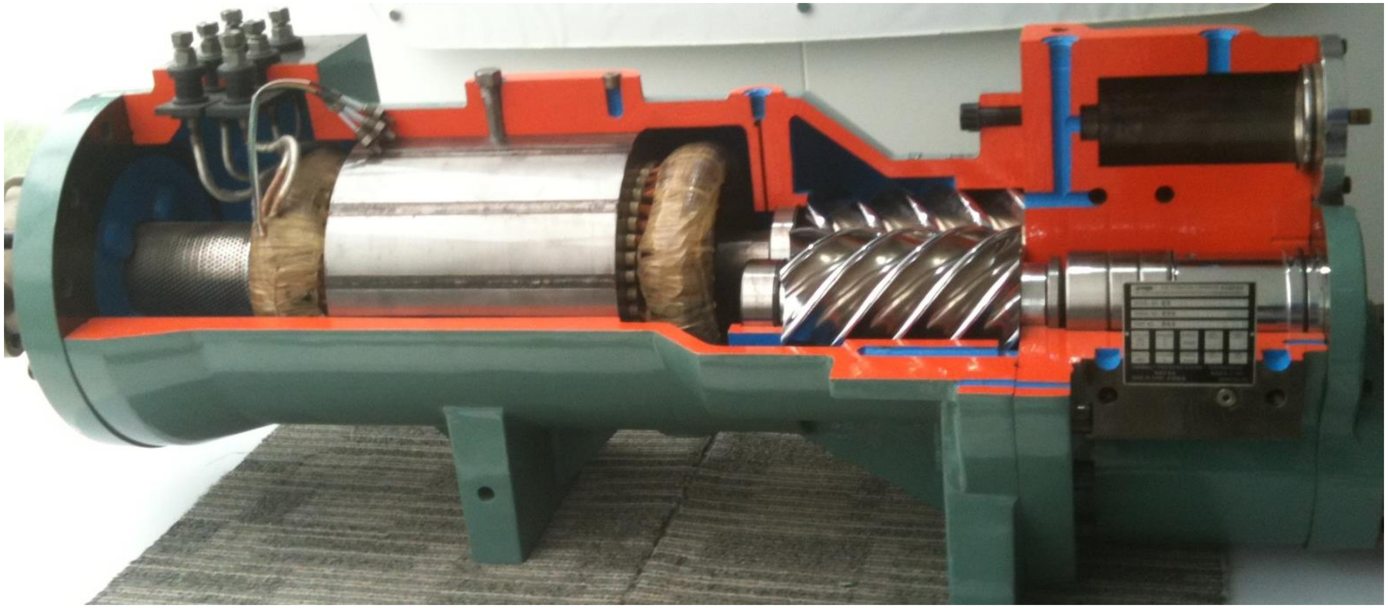
c) Refrigerant is compressed into two increasingly smaller pockets

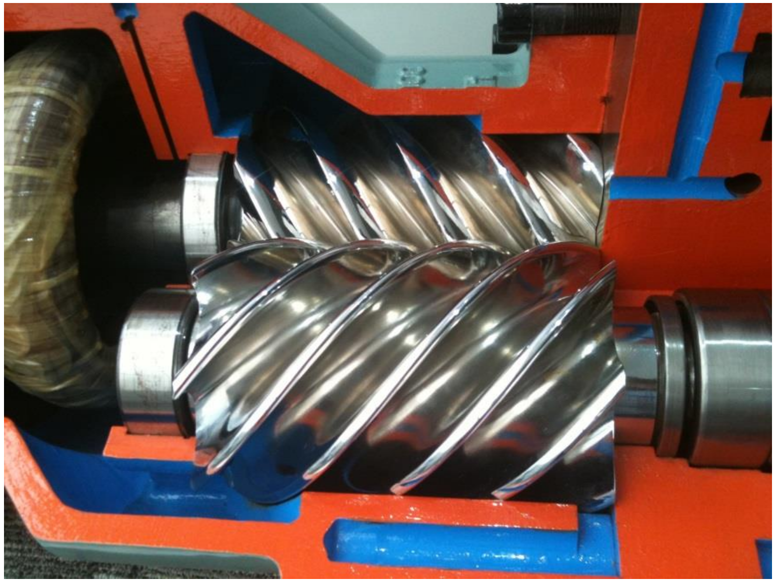
d) High pressure refrigerant is discharged at the center port

**Mechanism of a scroll compressor**

# Chiller with Screw Compressor

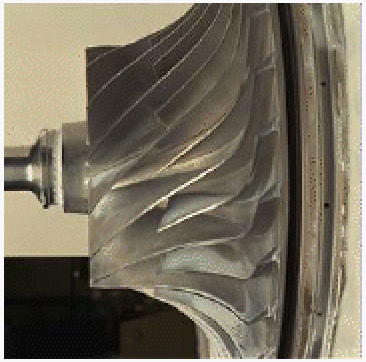


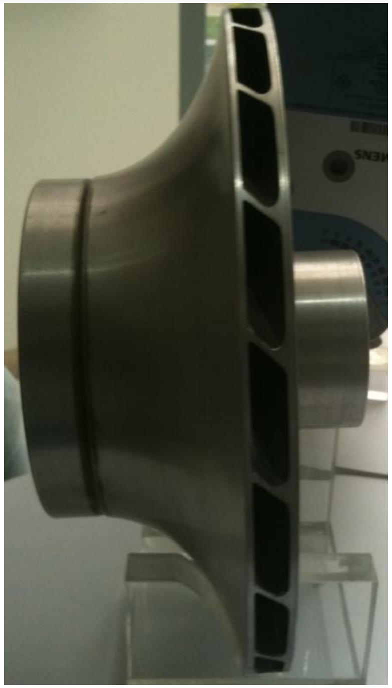




# Chiller with Centrifugal Compressor

Open-type compressor





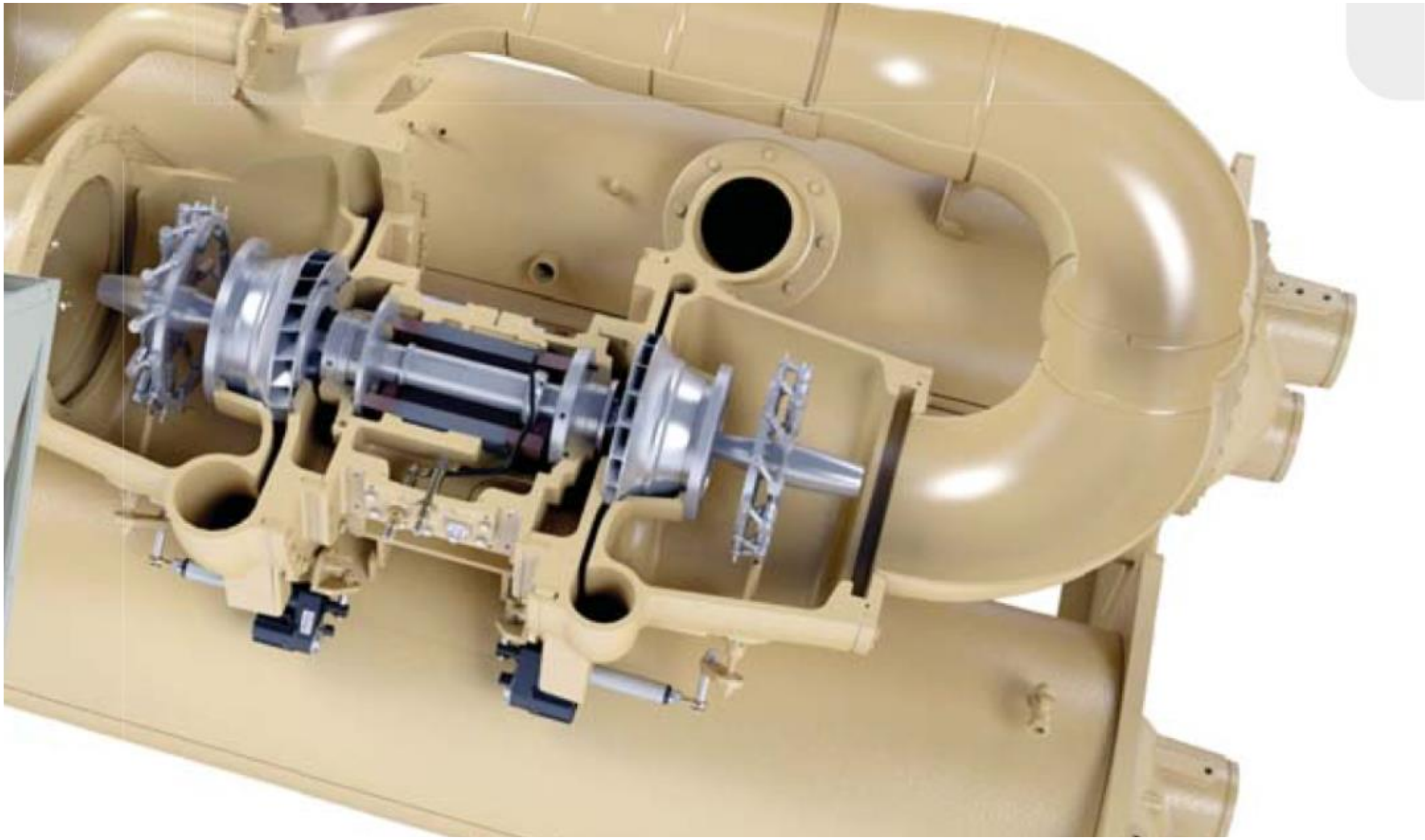
# Chiller with Centrifugal Compressor



Hermetic single compressor with inlet guide vane

# Chiller with Centrifugal Compressor

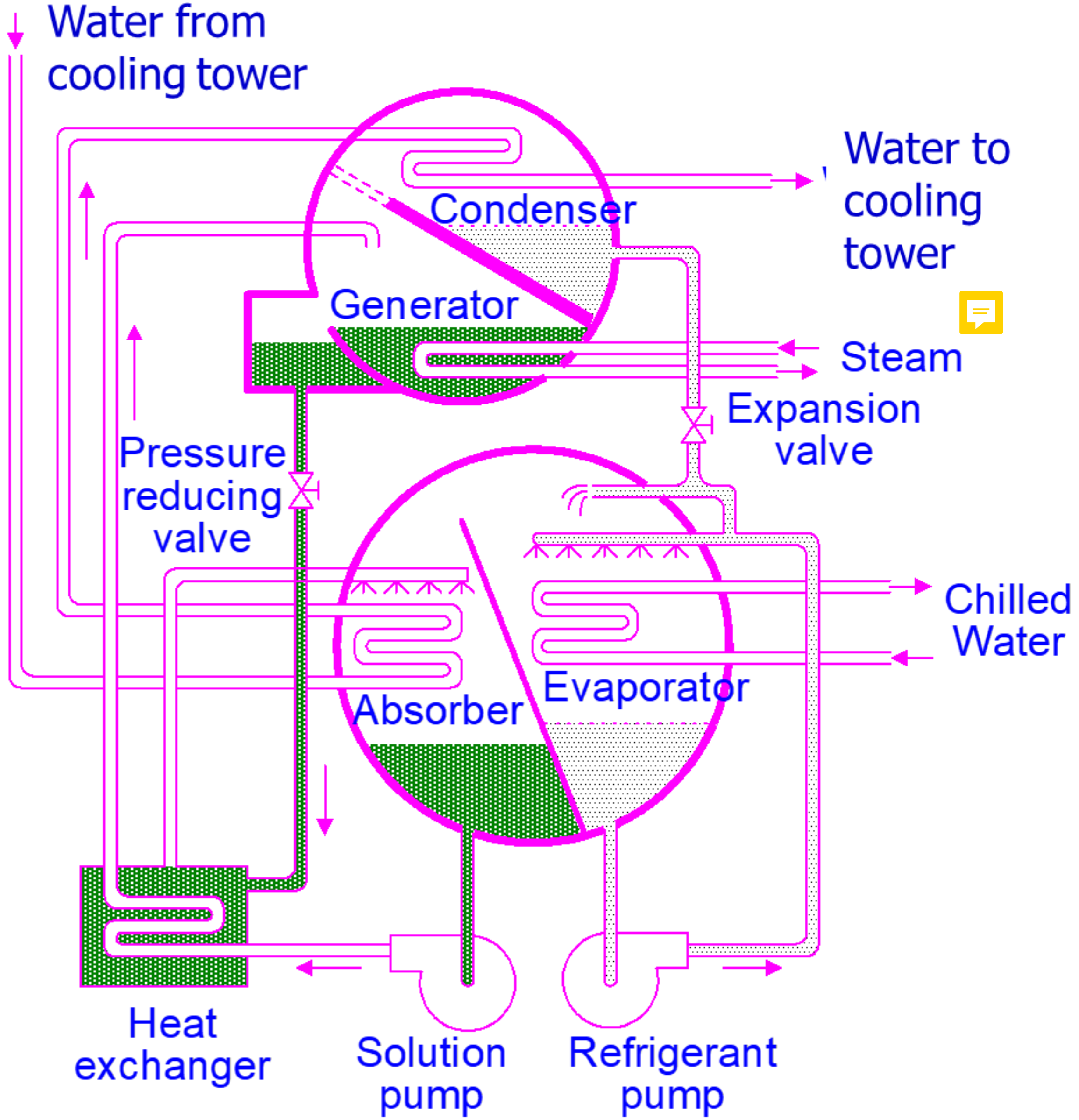




Hermetic twin compressors with inlet guide vanes

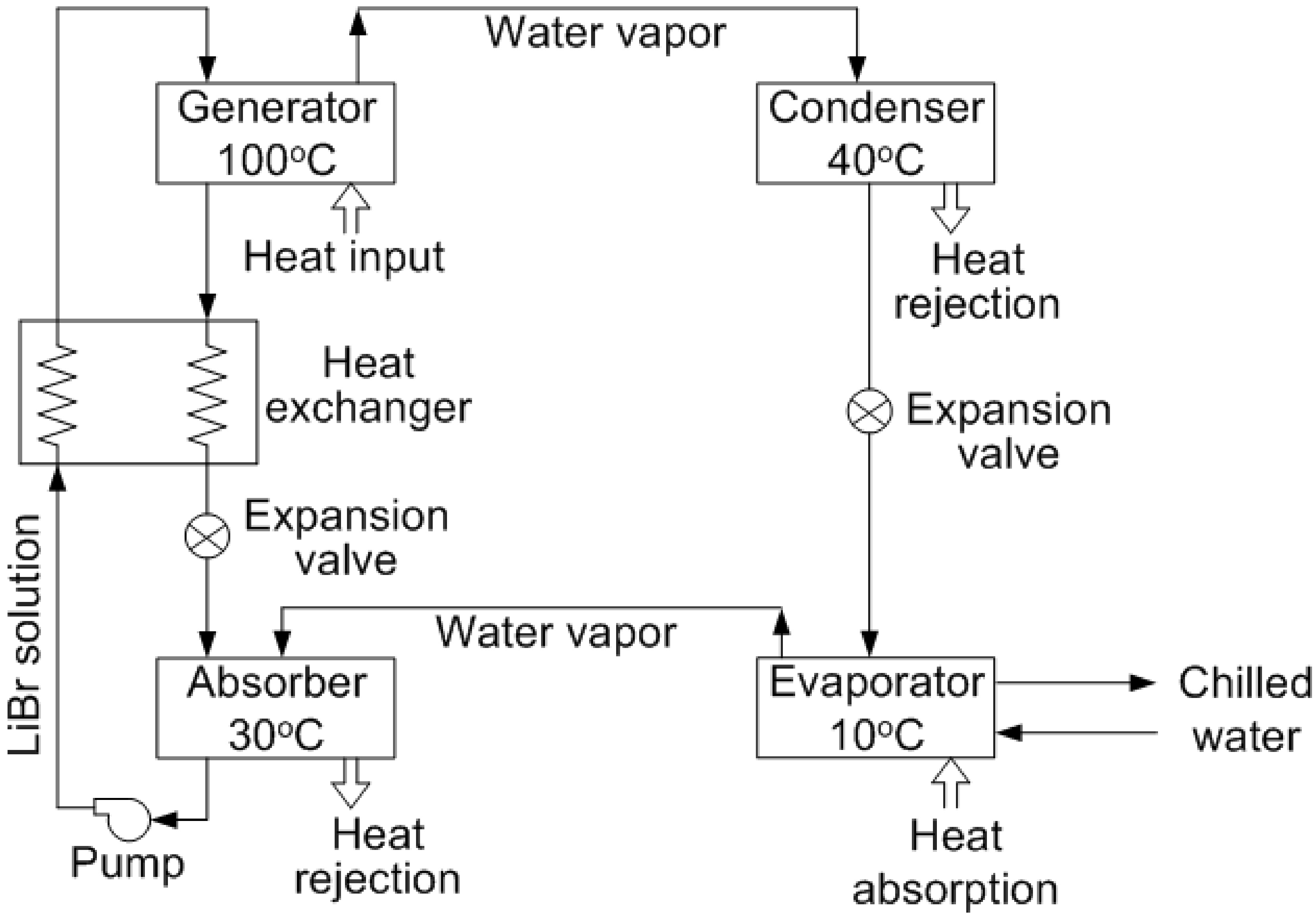
# Absorption Chiller





# Absorption Chiller





# Operating Efficiency of Chillers



**Operating efficiency of chillers depends on:**

1) Types of chillers
2) Rated efficiency
3) Part-load performance
4) Capacity to load match
5) Chilled water and condenser water temperatures
6) Subcooling of condenser
7) Condition of condenser tubes

# Types of Chillers



Based on condenser coil cooling system, chiller is classified as:

1) Air Cooled Chiller (ACC)
2) Water cooled Chiller (WCC)

- ➢ Convective heat transfer coefficient for water is higher than air, resulting condensing temperature and pressure is lower for WCC. Therefore, WCC is much more efficient than ACC

- ➢ Typical efficiency of (a) ACC ranges from 1.0 to 1.5 kW/RT and (b) WCC ranges from 0.5 to 0.6 kW/RT


**Air Cooled Chiller**

- ➢ First cost of WCC systems is higher than ACC systems. Extra initial cost can payback in few years due to the higher energy efficiency of WCC

- ➢ ACC have many applications because they do not need cooling towers, make-up water flow and plant rooms. ACC can be used to support small area (Example: Data center area) when WCC is off.

# Problem: Savings due to Replacement of ACC



Air conditioning of a building is provided using a 350 RT Air Cooled Chiller (ACC). Building cooling load from 8am to 10pm is shown in below table. Chiller present energy consumption can be calculated as:

| Operating hours | Number of hours | Cooling load, RT | Existing ACC efficiency, kW/RT | Present energy consumption, kWh |
|---|---|---|---|---|
| | A | B | C | A x B x C |
| 0800 to 0900 | 1 | 250 | 1.3 | 325 |
| 0900 t0 1000 | 1 | 250 | 1.3 | 325 |
| 1000 to 1100 | 1 | 275 | 1.28 | 352 |
| 1100 to 1200 | 1 | 275 | 1.28 | 352 |
| 1200 to 1300 | 1 | 300 | 1.25 | 375 |
| 1300 to 1400 | 1 | 350 | 1.2 | 420 |
| 1400 to 1500 | 1 | 300 | 1.25 | 375 |
| 1500 to 1600 | 1 | 300 | 1.25 | 375 |
| 1600 to 1700 | 1 | 300 | 1.25 | 375 |
| 1700 to 1800 | 1 | 250 | 1.3 | 325 |
| 1800 to 1900 | 1 | 250 | 1.3 | 325 |
| 1900 to 2000 | 1 | 250 | 1.3 | 325 |
| 2000 to 2100 | 1 | 200 | 1.4 | 280 |
| 2100 to 2200 | 1 | 200 | 1.4 | 280 |
| | | | **Total** | **4809** |

# Problem: Savings due to Replacement of ACC



If the ACC is replaced with a WCC having the following efficiency, compute the achievable energy savings for this replacement.

| Load (RT) | Efficiency (kW/RT) |
|---|---|
| 200 | 0.62 |
| 250 | 0.6 |
| 275 | 0.59 |
| 300 | 0.58 |
| 350 | 0.57 |

# Problem: Savings due to Replacement of ACC



| Operating hours | Number of hours | Cooling load, RT | Existing ACC efficiency, kW/RT | Present energy consumption, kWh | Proposed WCC efficiency, kW/RT | Proposed energy consumption, kWh |
|---|---|---|---|---|---|---|
| | A | B | C | A x B x C | D | A x B x D |
| 0800 to 0900 | 1 | 250 | 1.3 | 325 | 0.6 | 150 |
| 0900 t0 1000 | 1 | 250 | 1.3 | 325 | 0.6 | 150 |
| 1000 to 1100 | 1 | 275 | 1.28 | 352 | 0.59 | 162.25 |
| 1100 to 1200 | 1 | 275 | 1.28 | 352 | 0.59 | 162.25 |
| 1200 to 1300 | 1 | 300 | 1.25 | 375 | 0.58 | 174 |
| 1300 to 1400 | 1 | **350** | **1.2** | 420 | **0.57** | 199.5 |
| 1400 to 1500 | 1 | 300 | 1.25 | 375 | 0.58 | 174 |
| 1500 to 1600 | 1 | 300 | 1.25 | 375 | 0.58 | 174 |
| 1600 to 1700 | 1 | 300 | 1.25 | 375 | 0.58 | 174 |
| 1700 to 1800 | 1 | 250 | 1.3 | 325 | 0.6 | 150 |
| 1800 to 1900 | 1 | 250 | 1.3 | 325 | 0.6 | 150 |
| 1900 to 2000 | 1 | 250 | 1.3 | 325 | 0.6 | 150 |
| 2000 to 2100 | 1 | 200 | 1.4 | 280 | 0.62 | 124 |
| 2100 to 2200 | 1 | 200 | 1.4 | 280 | 0.62 | 124 |
| | | | **Total** | **4809** | | **2218** |

Energy savings = 4809 – 2218 = 2591 kWh/day

# Problem: Savings due to Replacement of ACC



Extra operating cost for WCC:

a) Operating condenser water pumps
b) Operating cooling tower fans
c) Use of make-up water for cooling tower

- Total power consumption for condenser water pumps and cooling towers ranges from 0.08 to 0.15 kW/RT
- Make-up water consumption for cooling tower: about 1 to 1.5% of circulating flow rate, or approximately 1 x $10^{-2}$ $m^3$/hr per RT

- Assume total power consumption for condenser water pumps and cooling towers = 0.12 kW/RT
- Make-up water consumption for cooling tower = 1 x $10^{-2}$ $m^3$/hr per RT

# Problem: Savings due to Replacement of ACC



| Operating hours | Number of hours | Cooling load, RT | Energy consumption for condenser water pumps and cooling towers, kWh | Make-up water consumption for cooling towers, $m^3$ |
|---|---|---|---|---|
| | A | B | A x B x 0.12 kW/RT | B x 1 x $10^{-2}$ |
| 0800 to 0900 | 1 | 250 | 30 | 2.5 |
| 0900 t0 1000 | 1 | 250 | 30 | 2.5 |
| 1000 to 1100 | 1 | 275 | 33 | 2.75 |
| 1100 to 1200 | 1 | 275 | 33 | 2.75 |
| 1200 to 1300 | 1 | 300 | 36 | 3 |
| 1300 to 1400 | 1 | **350** | **42** | 3.5 |
| 1400 to 1500 | 1 | 300 | 36 | 3 |
| 1500 to 1600 | 1 | 300 | 36 | 3 |
| 1600 to 1700 | 1 | 300 | 36 | 3 |
| 1700 to 1800 | 1 | 250 | 30 | 2.5 |
| 1800 to 1900 | 1 | 250 | 30 | 2.5 |
| 1900 to 2000 | 1 | 250 | 30 | 2.5 |
| 2000 to 2100 | 1 | 200 | 24 | 2 |
| 2100 to 2200 | 1 | 200 | 24 | 2 |
| | | **Total** | **450** | **37.5** |

# Problem: Savings due to Replacement of ACC



Extra electrical energy consumption by condenser water pumps and cooling towers = 450 kWh/day

Make-up water consumption for cooling tower = **37.5 m³/day**

Therefore, the net electrical energy savings = 2591 – 450 = **2141 kWh/day**

**Peak electrical demand savings :**

= Peak cooling load (RT) x difference in ACC and WCC efficiencies (kW/RT) – Peak cooling load (RT) x Combined efficiency of condenser water pump and cooling tower, kW/RT

= 350 x (1.2 – 0.57) - 350 x 0.12

= **178.5 kW**

# Problem: Savings due to Replacement of ACC



If the utility tariffs are:
Electricity usage = $0.27 / kWh
Peak demand = $8 / kW per month
Water usage = $1 / $m^3$

Net annual savings (based on operating 365 days a year)

= [(**2141** kWh/day x Electricity tariff) - (**37.5** $m^3$/day x water tariff)] x days/year + [**178.5** kW x monthly electricity demand charges x 12 months/year]

= [(2141 x 0.27) – (37.5 x 1)] x 365 + [178.5 x 8 x 12]

= $214,444 per year

# Problem

A 700 RT chiller is rated at 0.55 kW/RT at ARI conditions (chilled water supply temperature of 6.7°C, condenser water supply temperature of 29.4°C and maximum $\Delta$T of 5.6°C)

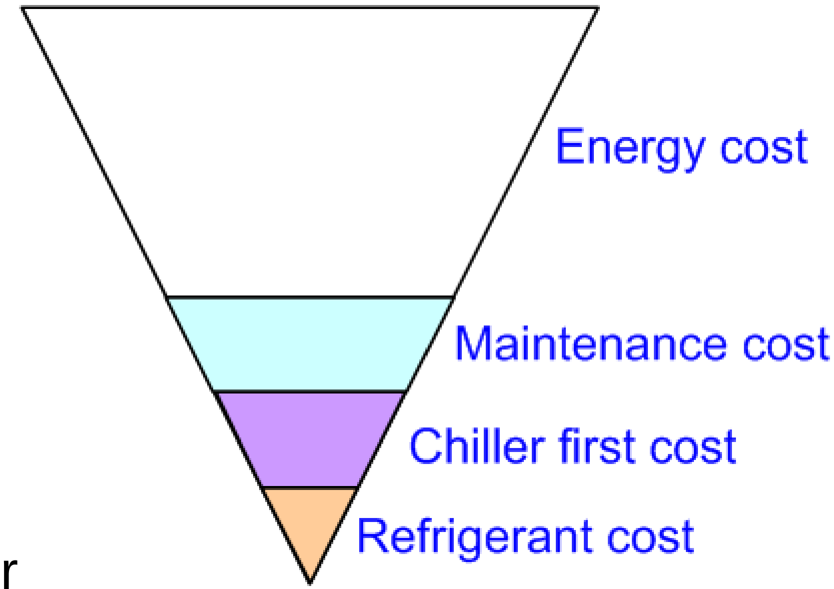
However, in actual operation, the efficiency is only 0.65 kW/RT

a) What are the possible reasons for the drop in efficiency ?

b) How can the efficiency be improved ?

# Chiller Efficiency and Life Cycle Costing

- Chiller rated (100% loading) efficiency ranges from 0.5 to 0.65 kW/RT
- Components of chiller life cycle cost:

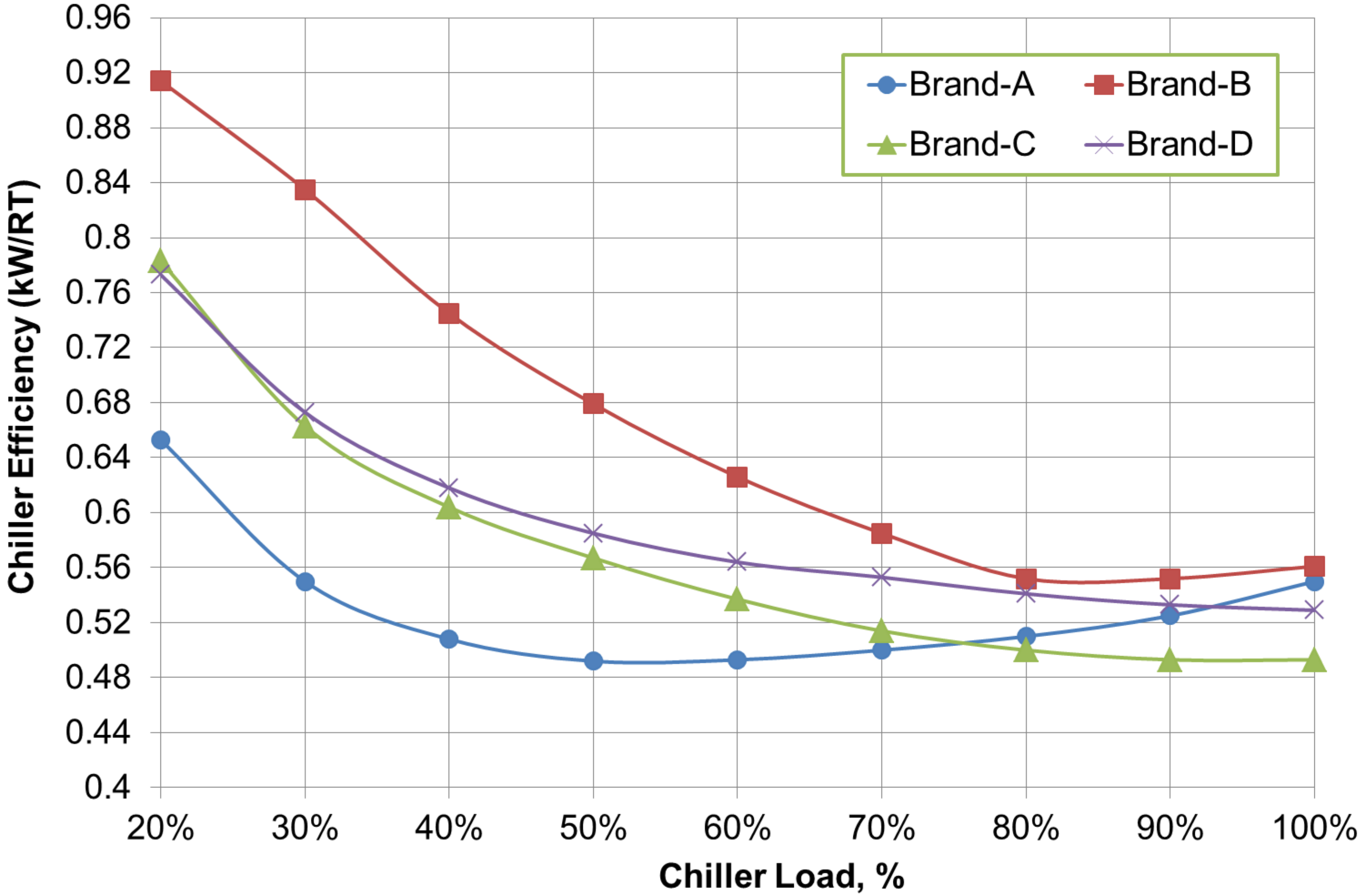



- Energy cost exceeds the first cost by 10 to 15 times over the operating life
- High efficiency chiller is expensive
- Extra initial cost of high efficiency chiller is pay back in about 3 to 5 years time

| | Hotel | | Industrial | | Office | | Retail | |
|---|---|---|---|---|---|---|---|---|
| Chiller efficiency (kW/RT) | 0.55 | 0.5 | 0.55 | 0.5 | 0.55 | 0.5 | 0.55 | 0.5 |
| Simple payback (years) | 3 | 3.6 | 3 | 3.6 | 4.8 | 5.7 | 3.9 | 4.7 |

# Chiller Sizing and Configuration

- Chiller operating efficiency depends on chiller loading
- Variation of chiller efficiency with loading for different brand chillers using different types of compressor and refrigerant:



# Chiller Sizing and Configuration



- To operate chiller plant in energy efficient manner, building cooling load profile needs to match with chiller energy efficient loading

- For existing buildings, cooling load profile of building can be measured using existing chiller plant

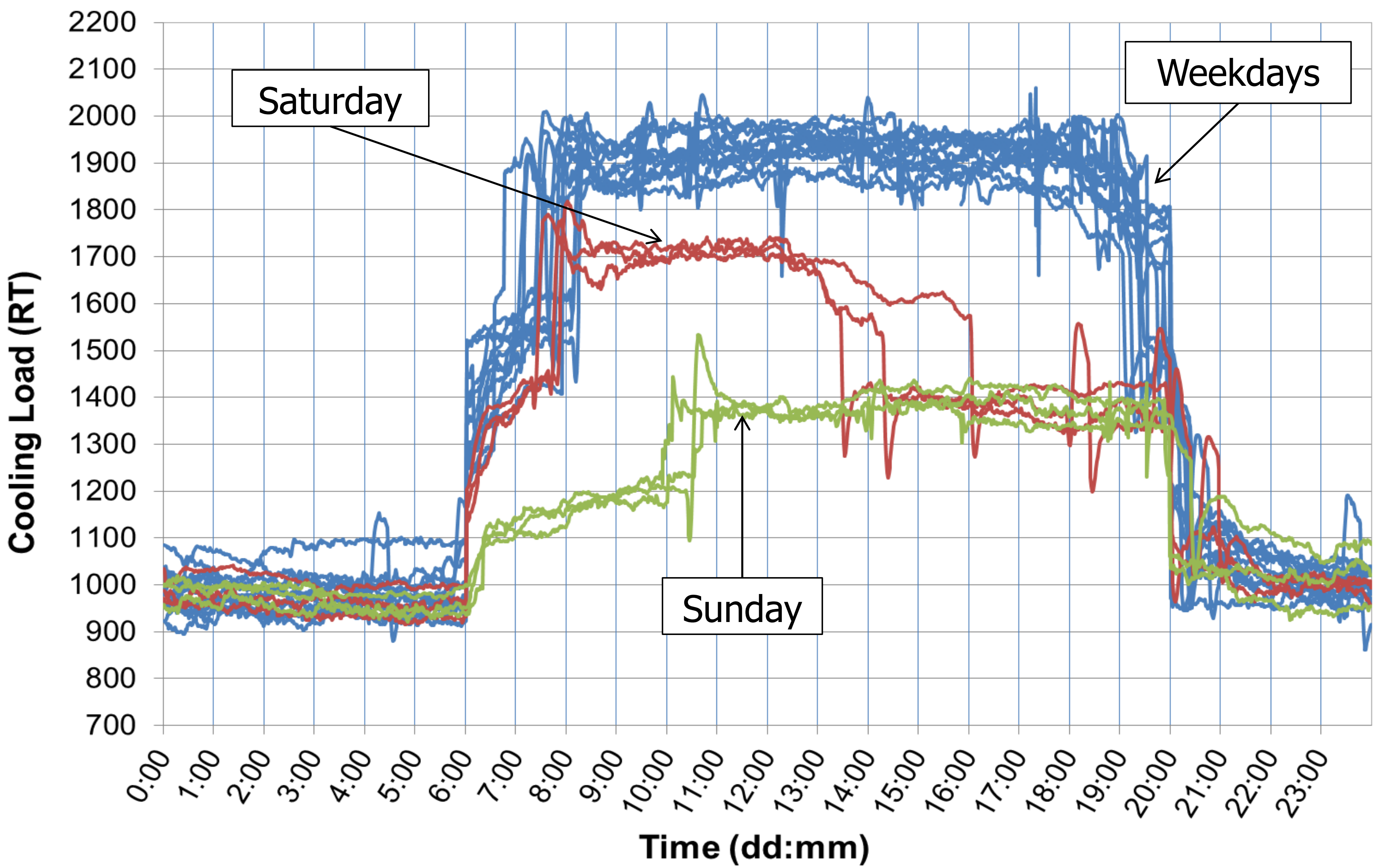
- For new buildings, cooling load profile of building is determined using building energy simulation. Often chiller capacity is oversized due to assumptions made in cooling load simulation and the selection of chiller based on expected peak load

- In many cases, this over-sizing is repeated when the chillers are replaced many years later

# Chiller Sizing and Configuration

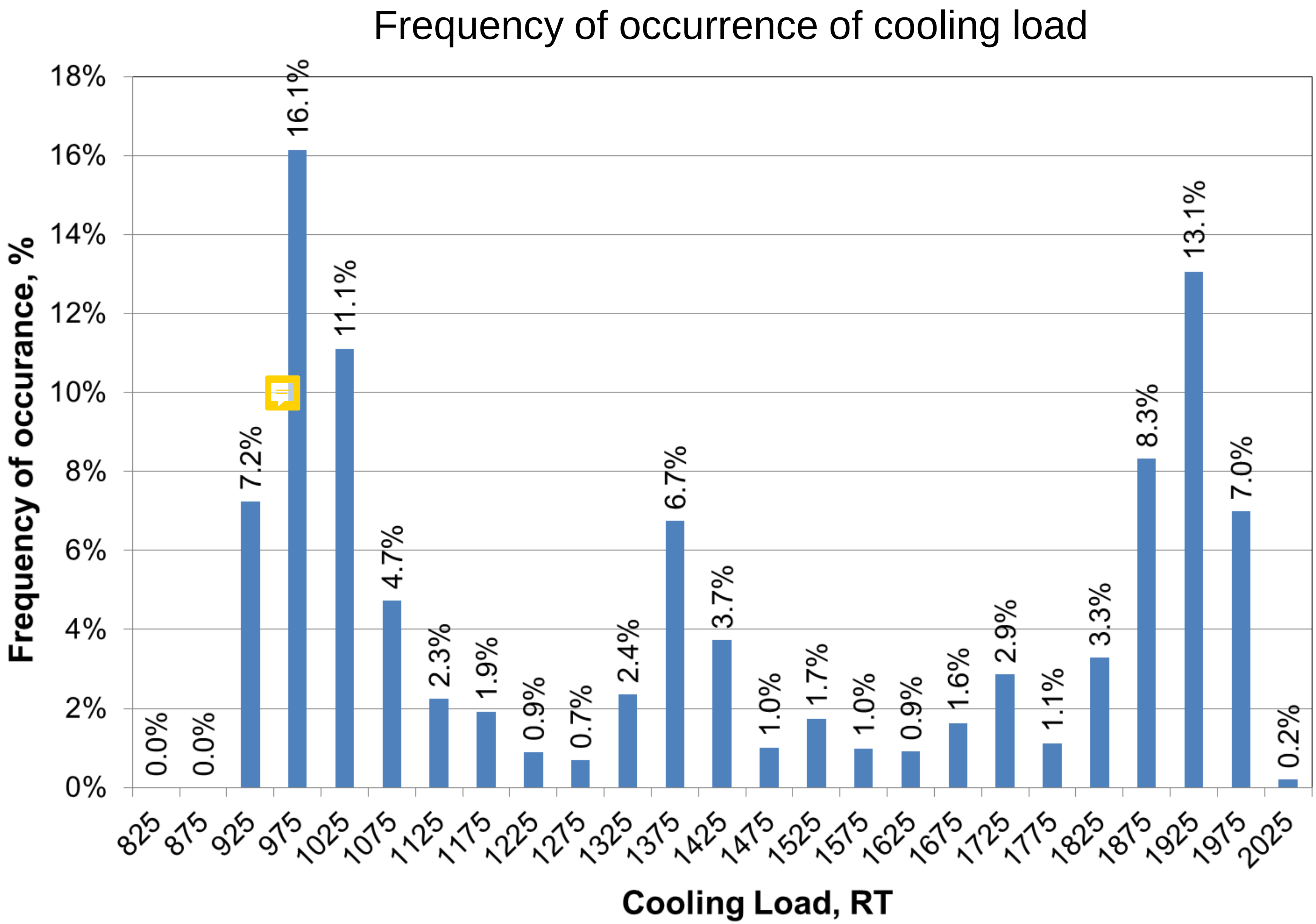


**Example:** Cooling load profile of a building is given below:



# Chiller Sizing and Configuration





# Chiller Sizing and Configuration



To satisfy the cooling load, three different chiller combinations are considered which are: (a) 1 x 2050 RT, (b) 2 x 1100 RT and (c) 1 x 500 RT + 2 x 800 RT. Part load efficiency for the selected chillers are shown below. Which chiller combination will you? Justify your selection

**Chiller part load performance data**

| Chiller loading, % | 2050 RT | 1100 RT | 800 RT | 500 RT |
|---|---|---|---|---|
| 100 | 0.528 | 0.525 | 0.532 | 0.56 |
| 90 | 0.521 | 0.524 | 0.531 | 0.54 |
| 80 | 0.522 | 0.524 | 0.533 | 0.52 |
| 70 | 0.529 | 0.523 | 0.534 | 0.51 |
| 60 | 0.542 | 0.545 | 0.538 | 0.5 |
| 50 | 0.566 | 0.558 | 0.563 | 0.51 |
| 40 | 0.6 | 0.586 | 0.59 | 0.52 |
| 30 | 0.653 | 0.639 | 0.641 | 0.57 |
| 20 | 0.745 | 0.755 | 0.754 | 0.68 |

# Chiller Sizing and Configuration



- Consumption of energy for 1 x 2050 RT chiller option:

| Av RT | Occurrence | Operating hours/day | Operating chiller | Part Load | Chiller Eff, kW/RT | Energy consumption, kWh |
|---|---|---|---|---|---|---|
| A | B | C = B x 24 | D | E = A / D | F | A x C x F |
| 925 | 0.072 | 1.74 | 1x2050 | 45.1 | 0.583 | 938.1 |
| 975 | 0.161 | 3.87 | 1x2050 | 47.6 | 0.574 | 2167.7 |
| 1025 | 0.111 | 2.66 | 1x2050 | 50.0 | 0.566 | 1545.0 |
| 1075 | 0.047 | 1.14 | 1x2050 | 52.4 | 0.56 | 684.8 |
| 1125 | 0.023 | 0.54 | 1x2050 | 54.9 | 0.554 | 336.7 |
| 1175 | 0.019 | 0.46 | 1x2050 | 57.3 | 0.548 | 294.7 |
| 1225 | 0.009 | 0.22 | 1x2050 | 59.8 | 0.542 | 143.2 |
| 1275 | 0.007 | 0.17 | 1x2050 | 62.2 | 0.539 | 114.6 |
| 1325 | 0.024 | 0.57 | 1x2050 | 64.6 | 0.536 | 402.3 |
| 1375 | 0.067 | 1.62 | 1x2050 | 67.1 | 0.533 | 1187.1 |
| 1425 | 0.037 | 0.89 | 1x2050 | 69.5 | 0.53 | 675.0 |
| 1475 | 0.010 | 0.24 | 1x2050 | 72.0 | 0.528 | 187.1 |
| 1525 | 0.017 | 0.42 | 1x2050 | 74.4 | 0.526 | 335.9 |
| 1575 | 0.010 | 0.24 | 1x2050 | 76.8 | 0.524 | 196.7 |
| 1625 | 0.009 | 0.22 | 1x2050 | 79.3 | 0.522 | 185.3 |
| 1675 | 0.016 | 0.39 | 1x2050 | 81.7 | 0.522 | 343.2 |
| 1725 | 0.029 | 0.69 | 1x2050 | 84.1 | 0.522 | 617.9 |
| 1775 | 0.011 | 0.27 | 1x2050 | 86.6 | 0.521 | 249.0 |
| 1825 | 0.033 | 0.79 | 1x2050 | 89.0 | 0.521 | 749.0 |
| 1875 | 0.083 | 2.00 | 1x2050 | 91.5 | 0.522 | 1953.6 |
| 1925 | 0.131 | 3.13 | 1x2050 | 93.9 | 0.524 | 3161.8 |
| 1975 | 0.070 | 1.68 | 1x2050 | 96.3 | 0.525 | 1739.7 |
| 2025 | 0.003 | 0.07 | 1x2050 | 98.8 | 0.527 | 70.6 |
| **Total** | **1.000** | **24.00** | | | | **18,279** |

Average daily energy consumption = 18,279 kWh / day

Annual energy consumption = 18,279 x 365 = 6,671,835 kWh / year

# Chiller Sizing and Configuration



- Consumption of energy for 2 x 1100 RT chiller option:

| Av RT | Occurrence | Operating hours/day | Operating chiller | Part Load | Chiller Eff, kW/RT | Energy consumption , kWh |
|---|---|---|---|---|---|---|
| A | B | C = B x 24 | D | E = A / D | F | A x C x F |
| 925 | 0.072 | 1.74 | 1x1100 | 84.1 | 0.524 | 843.1 |
| 975 | 0.161 | 3.87 | 1x1100 | 88.6 | 0.524 | 1978.8 |
| 1025 | 0.111 | 2.66 | 1x1100 | 93.2 | 0.524 | 1430.4 |
| 1075 | 0.047 | 1.14 | 1x1100 | 97.7 | 0.525 | 642.0 |
| 1125 | 0.023 | 0.54 | 2x1100 | 51.1 | 0.557 | 338.5 |
| 1175 | 0.019 | 0.46 | 2x1100 | 53.4 | 0.554 | 298.0 |
| 1225 | 0.009 | 0.22 | 2x1100 | 55.7 | 0.551 | 145.6 |
| 1275 | 0.007 | 0.17 | 2x1100 | 58.0 | 0.548 | 116.5 |
| 1325 | 0.024 | 0.57 | 2x1100 | 60.2 | 0.545 | 409.1 |
| 1375 | 0.067 | 1.62 | 2x1100 | 62.5 | 0.54 | 1202.7 |
| 1425 | 0.037 | 0.89 | 2x1100 | 64.8 | 0.534 | 680.1 |
| 1475 | 0.010 | 0.24 | 2x1100 | 67.0 | 0.53 | 187.8 |
| 1525 | 0.017 | 0.42 | 2x1100 | 69.3 | 0.525 | 335.3 |
| 1575 | 0.010 | 0.24 | 2x1100 | 71.6 | 0.523 | 196.4 |
| 1625 | 0.009 | 0.22 | 2x1100 | 73.9 | 0.523 | 185.7 |
| 1675 | 0.016 | 0.39 | 2x1100 | 76.1 | 0.524 | 344.5 |
| 1725 | 0.029 | 0.69 | 2x1100 | 78.4 | 0.524 | 620.2 |
| 1775 | 0.011 | 0.27 | 2x1100 | 80.7 | 0.524 | 250.4 |
| 1825 | 0.033 | 0.79 | 2x1100 | 83.0 | 0.524 | 753.3 |
| 1875 | 0.083 | 2.00 | 2x1100 | 85.2 | 0.524 | 1961.1 |
| 1925 | 0.131 | 3.13 | 2x1100 | 87.5 | 0.524 | 3161.8 |
| 1975 | 0.070 | 1.68 | 2x1100 | 89.8 | 0.524 | 1736.4 |
| 2025 | 0.003 | 0.07 | 2x1100 | 92.0 | 0.524 | 70.2 |
| **Total** | **1.000** | **24.00** | | | | **17,888** |

Average daily energy consumption = 17,888 kWh / day

Annual energy consumption = 17,888 x 365 = 6,529,120 kWh / year

# Chiller Sizing and Configuration



- Consumption of energy for 2 x 800 + 1 x 500 RT chiller option:

Average daily energy consumption = 18,022 kWh / day

Annual energy consumption = 18,022 x 365 = 6,578,030 kWh / year

| Av RT | Occurrence | Operating hours/day | Operating chiller | Part Load | Chiller Eff, kW/RT | Energy consumption, kWh |
|---|---|---|---|---|---|---|
| A | B | C = B x 24 | D | E = A / D | F | A x C x F |
| 925 | 0.072 | 1.74 | 1x800+1x500 | 71.2 | 0.525 | 844.7 |
| 975 | 0.161 | 3.87 | 1x800+1x500 | 75.0 | 0.526 | 1986.4 |
| 1025 | 0.111 | 2.66 | 1x800+1x500 | 78.8 | 0.528 | 1441.3 |
| 1075 | 0.047 | 1.14 | 1x800+1x500 | 82.7 | 0.53 | 648.1 |
| 1125 | 0.023 | 0.54 | 1x800+1x500 | 86.5 | 0.532 | 323.3 |
| 1175 | 0.019 | 0.46 | 1x800+1x500 | 90.4 | 0.535 | 287.8 |
| 1225 | 0.009 | 0.22 | 1x800+1x500 | 94.2 | 0.538 | 142.2 |
| 1275 | 0.007 | 0.17 | 1x800+1x500 | 98.1 | 0.541 | 115.0 |
| 1325 | 0.024 | 0.57 | 2x800 | 82.8 | 0.532 | 399.3 |
| 1375 | 0.067 | 1.62 | 2x800 | 85.9 | 0.532 | 1184.9 |
| 1425 | 0.037 | 0.89 | 2x800 | 89.1 | 0.531 | 676.3 |
| 1475 | 0.010 | 0.24 | 2x800 | 92.2 | 0.531 | 188.1 |
| 1525 | 0.017 | 0.42 | 2x800 | 95.3 | 0.532 | 339.8 |
| 1575 | 0.010 | 0.24 | 2x800 | 98.4 | 0.532 | 199.8 |
| 1625 | 0.009 | 0.22 | 2x800+1x500 | 77.4 | 0.529 | 187.8 |
| 1675 | 0.016 | 0.39 | 2x800+1x500 | 79.8 | 0.53 | 348.4 |
| 1725 | 0.029 | 0.69 | 2x800+1x500 | 82.1 | 0.531 | 628.5 |
| 1775 | 0.011 | 0.27 | 2x800+1x500 | 84.5 | 0.531 | 253.7 |
| 1825 | 0.033 | 0.79 | 2x800+1x500 | 86.9 | 0.532 | 764.8 |
| 1875 | 0.083 | 2.00 | 2x800+1x500 | 89.3 | 0.533 | 1994.7 |
| 1925 | 0.131 | 3.13 | 2x800+1x500 | 91.7 | 0.534 | 3222.1 |
| 1975 | 0.070 | 1.68 | 2x800+1x500 | 94.0 | 0.535 | 1772.8 |
| 2025 | 0.003 | 0.07 | 2x800+1x500 | 96.4 | 0.537 | 72.0 |
| **Total** | **1.000** | **24.00** | | | | **18,022** |

# Chiller Sizing and Configuration



**Comparison of energy consumption for the different combinations of chillers**

| Chiller combinations | Daily average energy consumption, kWh/day | Annual energy consumption, kWh/year |
|---|---|---|
| 1 x 2050 RT | 18,279 | 6,671,835 |
| **2 x 1100 RT** | **17,888** | **6,529,120** |
| 2 x 800 + 1 x 500 RT | 18,022 | 6,578,030 |

- Other advantages and disadvantages of proposed chiller combinations?

# Chillers for Off-Peak Operation

- Off-peak period cooling load is very small in comparison to peak period
- Example: Night time cooling load could be very small in comparison to the day time cooling load
- Dedicated small “Off-peak chillers” can be used to maintain a good chiller during off-peak period

**Example**

- Peak period (8am to 10pm) cooling load: 1500 to 2000 RT
- Off-peak period (10 pm to 8 am) cooling load: 200 to 250 RT
- Presently 600 RT chiller is used to provide cooling during off-peak period and the chiller operating efficiency is 1 to 1.2 kW/RT
- Calculate the savings achievable if a new 300 RT chiller of efficiency 0.56 to 0.58 kW/RT (when load is 200 to 250 RT) is used to provide cooling during off-peak period.

# Chillers for Off-Peak Operation



| Time | Hrs/day | Cooling load (RT) | Present chiller efficiency (kW/RT) | Present chiller consumption (kWh/day) | Proposed chiller efficiency (kW/RT) | Proposed chiller consumption (kWh/day) |
|---|---|---|---|---|---|---|
| | A | B | C | A x B X C | D | A x B X D |
| 2200 to 2300 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| 2300 to 2400 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| 0000 to 0100 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| 0100 to 0200 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| 0200 to 0300 | 1 | 200 | 1.2 | 240 | 0.58 | 116 |
| 0300 to 0400 | 1 | 200 | 1.2 | 240 | 0.58 | 116 |
| 0400 to 0500 | 1 | 200 | 1.2 | 240 | 0.58 | 116 |
| 0500 to 0600 | 1 | 200 | 1.2 | 240 | 0.58 | 116 |
| 0600 to 0700 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| 0700 to 0800 | 1 | 250 | 1 | 250 | 0.56 | 140 |
| Total | 10 | | | **2460** | | **1304** |

**Energy savings = 2460 – 1304 = 1,156 kWh/day**

# Consolidation of Chiller Plants



- Chiller plant energy consumption can be reduced or chiller performance can be improved through consolidation of chiller plant

- Possible opportunities:
  - Different buildings within one facility having different chiller plants (Example: Different blocks of NUS)
  - Tower block (office area) and podium block (retail area) are serving by two separate chiller plants
  - Standalone systems serving specific areas

- Larger scale application is District Cooling Systems

# Chiller Sequencing Strategies



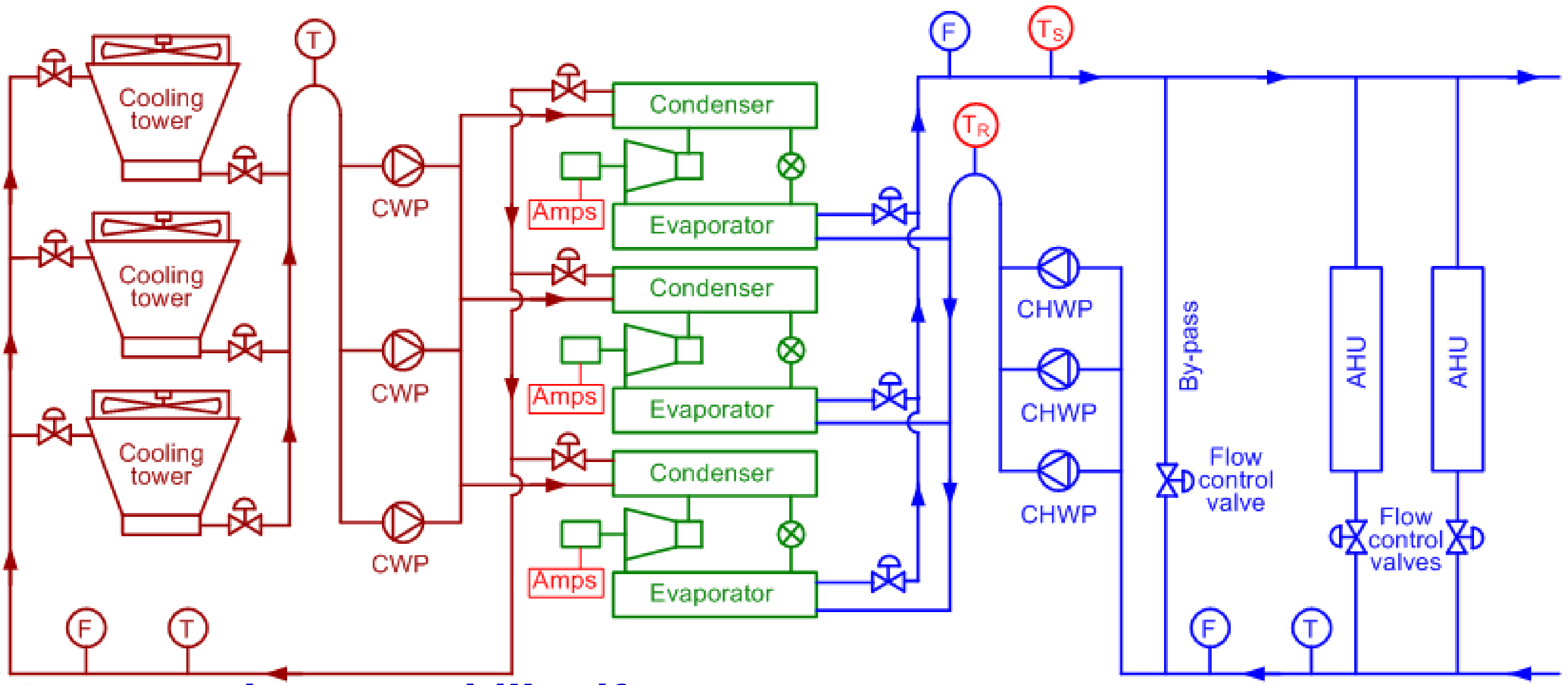
- Main objective of chiller sequencing is to select which chiller or set of chillers to be operated to support building load in energy an efficient manner

- During sequencing of chillers, the selected chillers need to satisfy the followings:
    - Building cooling load
    - Chilled water flow requirements: To ensure enough chilled water will flow to each AHU
    - Chilled water set-point requirements: To ensure AHUs can provide the required sensible and latent cooling

- Since chiller capacity and compressor power consumption change with the change of chilled water and condenser water supply temperature, compressor power (kW) should also be considered for sequencing to protect the compressor

# Chiller Sequencing for Primary Pumping System






**Start another one chiller if:**

- $T_S$ is greater than chilled water pre-set supply temperature

**Or**

Cooling load = Chiller capacity

And

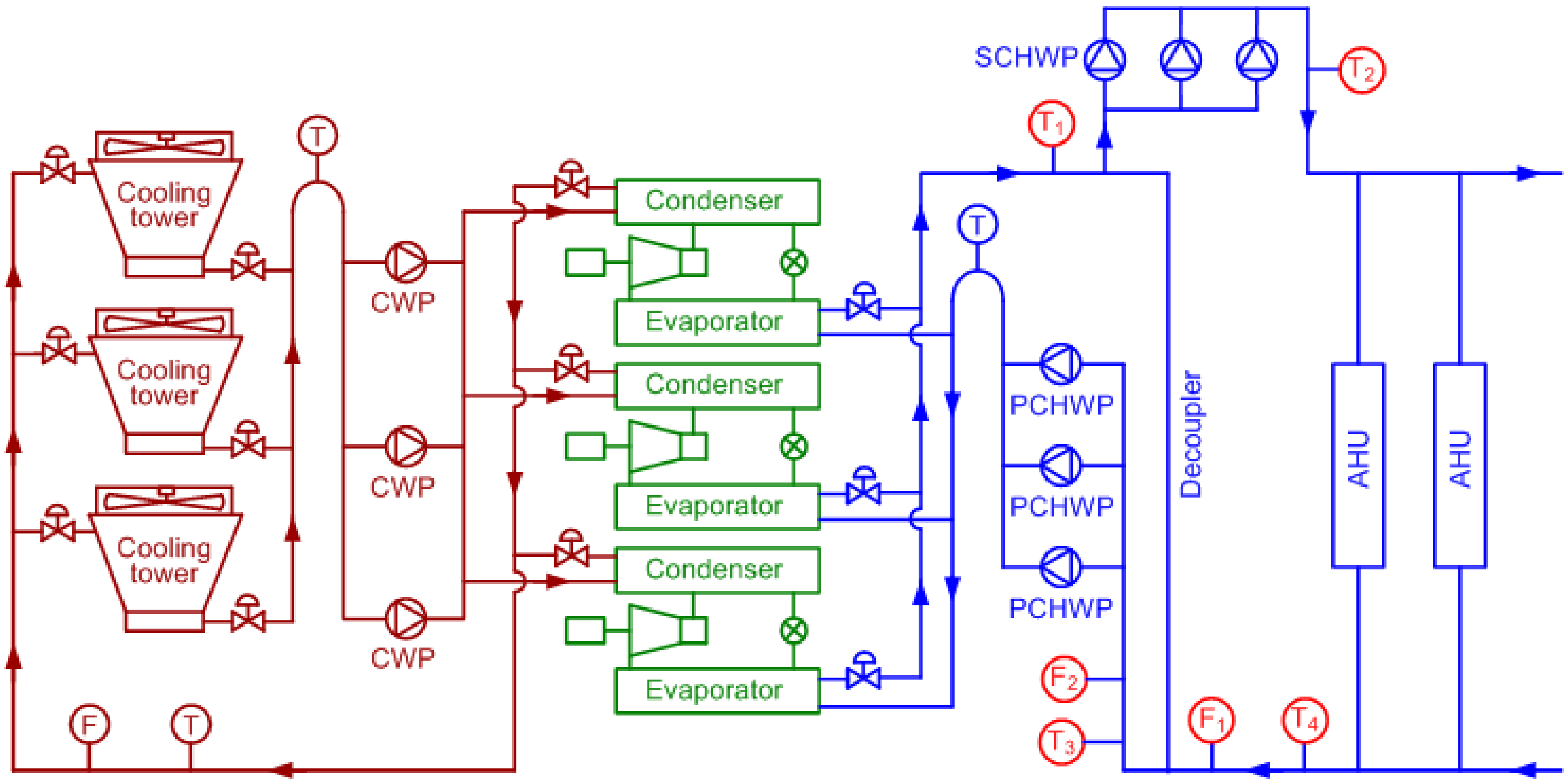
Compressor current ≥ Full load current

**Stop one chiller if:**

- Cooling load can be supported by operating 1 no. less chiller
- Monitor to ensure $T_S$ is not greater than set point

# Chiller Sequencing for Primary-Secondary Pumping System






**Start another one chiller if:**

- $T_1$ is greater than chilled water pre-set supply temperature

**Or**

Secondary flow $F_1$ > Primary flow $F_2$

**Stop one chiller if:**

- Cooling load can be supported by operating 1 no. less chiller
- Flow in decoupler pipe is about 110% of design flow of one operating chiller

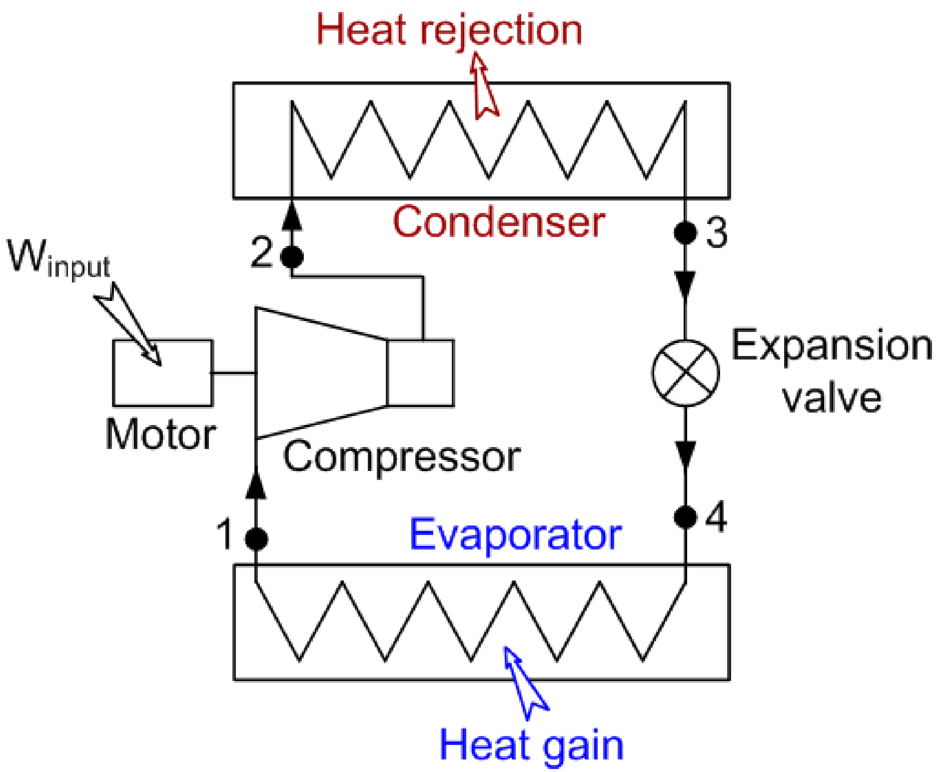
# Chiller Sequencing Strategies

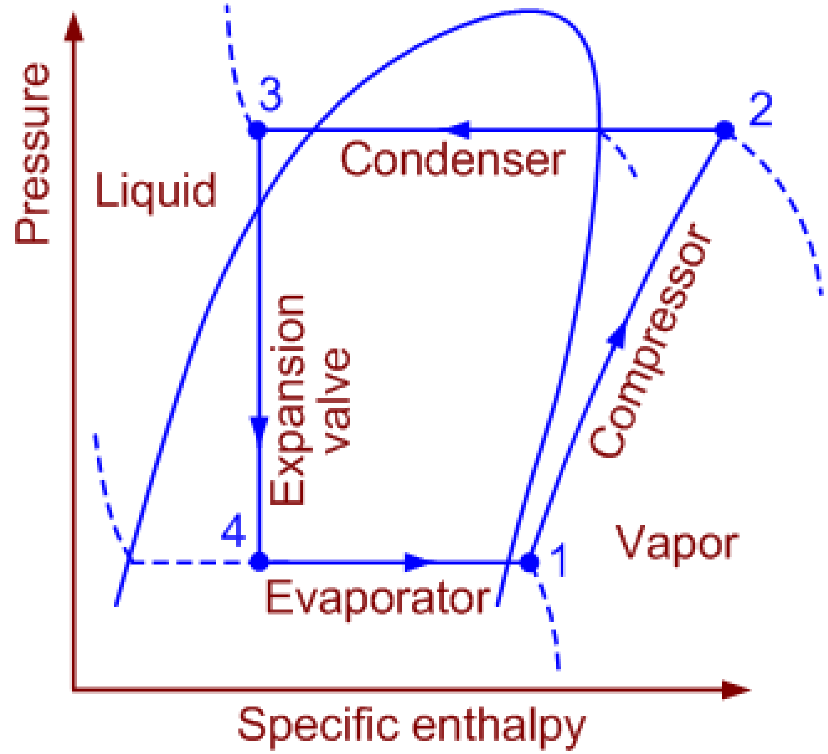


Chiller plant energy efficiency can be optimized further by:

- Sequencing chillers based on optimum part load efficiency
- Analyzing chiller performance characteristics under variable chilled and condenser water flow rate and temperature
- Analyzing pumps performance characteristics and using appropriate operating and control strategies
- Analyzing cooling tower and fan performance characteristics and using appropriate operating and control strategies
- Analyzing performance characteristics of AHUs, chilled water flow and temperature requirements for AHUs, air conditioning space temperature and Relative Humidity (RH) and fresh air flow requirements

# Effect of Chilled and Condenser Water Temperature Reset



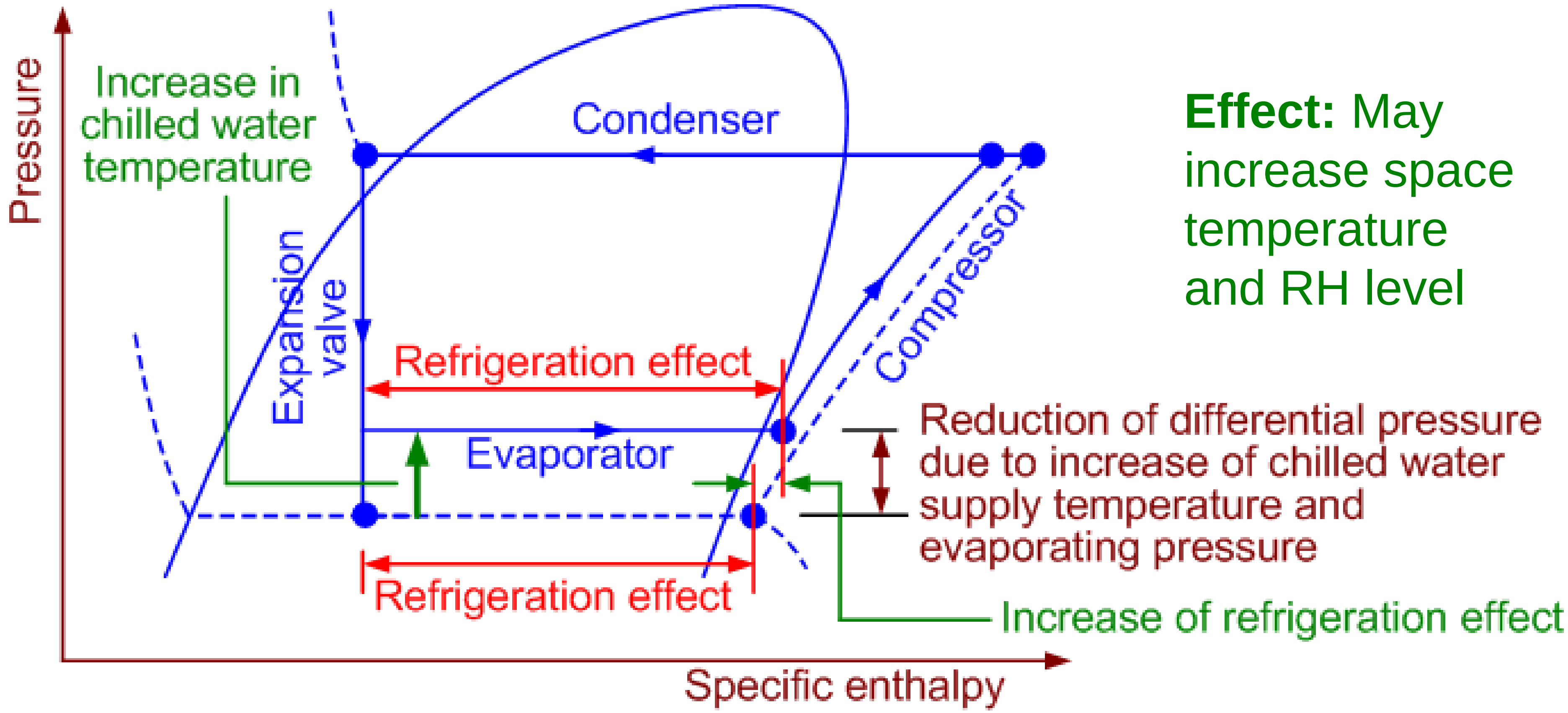




Power consumption of compressor = Output power / overall efficiency

Power consumption of compressor $\propto \dfrac{V\left(P_{condenser} - P_{evaporator}\right)}{\eta_c \eta_m \eta_g}$

Refrigeration effect per kg of refrigerant flow = $h_1 - h_4$

# Effect of Chilled Water Temperature Reset

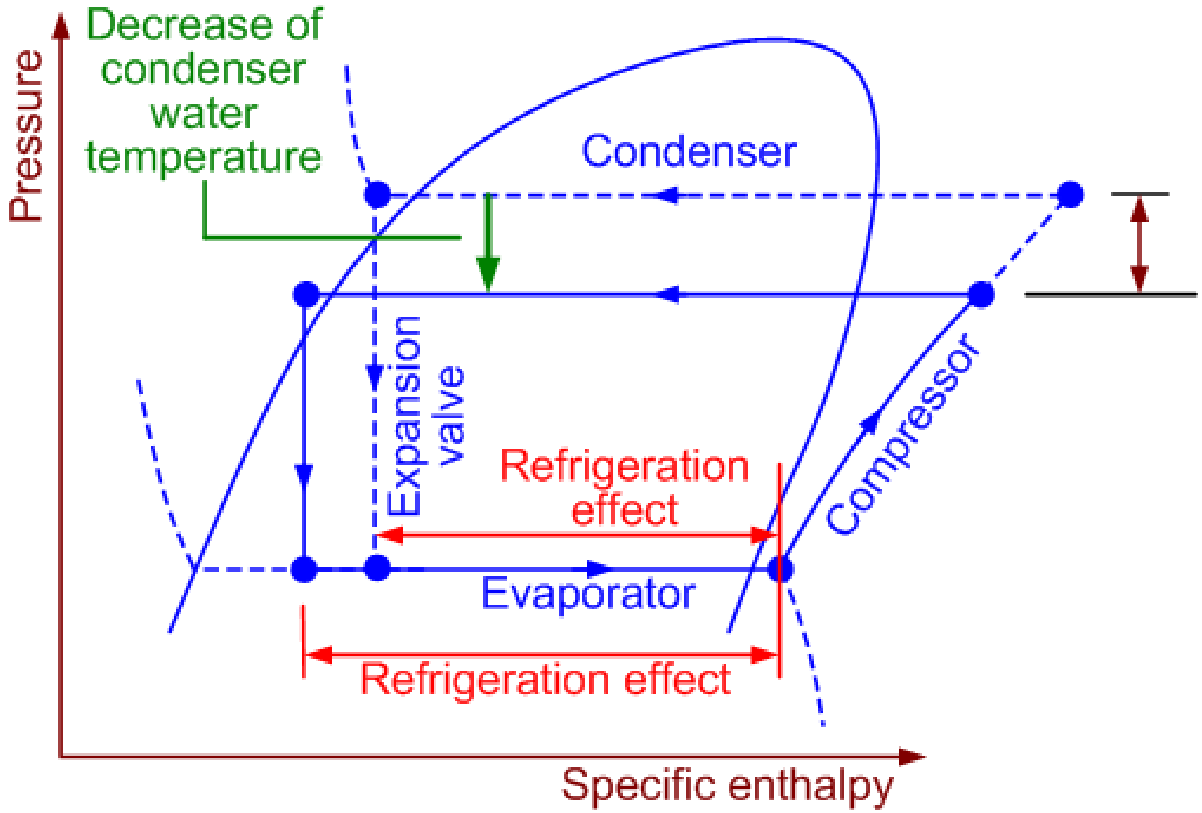



**Effect:** May increase space temperature and RH level

- Value of ($P_{condenser} - P_{evaporator}$) drops resulting drop of compressor input power
- Refrigeration effect per kg of refrigerant flow increases resulting improve of chiller efficiency kW/RT

# Effect of Condenser Water Temperature Reset






Reduction of differential pressure due to decrease of condenser water temperature and refrigerant condensing pressure

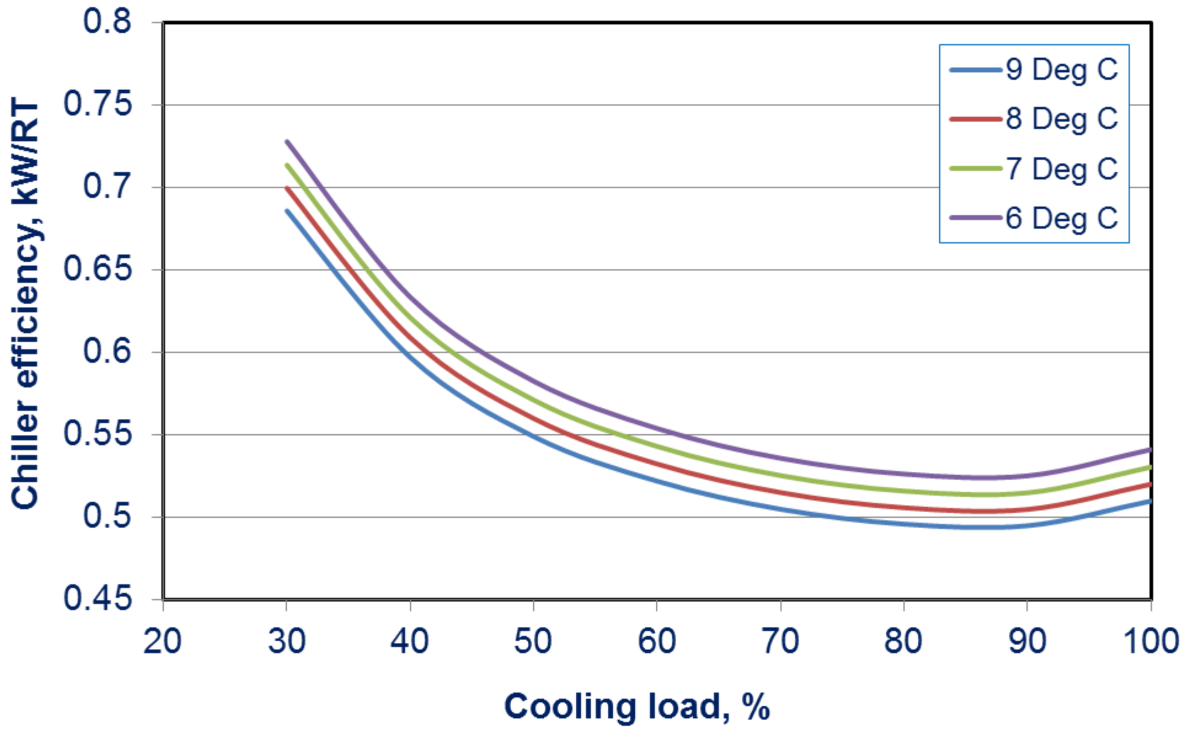
**Effect:** Cooling tower power consumption will increase

- Value of ($P_{condenser} - P_{evaporator}$) drops resulting drop of compressor input power
- Refrigeration effect per kg of refrigerant flow increases resulting improve of chiller efficiency kW/RT

# Reset of Chilled Water Supply Temperature



For every 1$^{o}$C increase of chilled water temperature, chiller efficiency is improved by 2% to 3% due to the reduction of compressor lift and increase of cooling capacity




- During part load operation, chilled water temperature can be reset upwards
- Chilled water requirement may increase for CAV AHUs and therefore higher pumping power if using variable speed pumping

# Example: Reset of Chilled Water Supply Temperature



Rated efficiency of a chiller of 1000 RT capacity at 7$^{o}$C is 0.51 kW/RT

If the chilled water supply temperature is increased to 8.5$^{o}$C, the chiller efficiency will improve to

$$0.51 \text{ kW/RT} \times (1 - 0.03) = 0.4947 \text{ kW/RT}$$

(Assuming 3% improvement of chiller efficiency due to increase of chilled water temperature 8.5 – 7 = 1.5$^{o}$C)

If chiller operates at 1000 RT for 10 hrs/day and 350 days/year

Annual energy saving $= (0.51 - 0.4947) \times 1000 \times 10 \times 350$

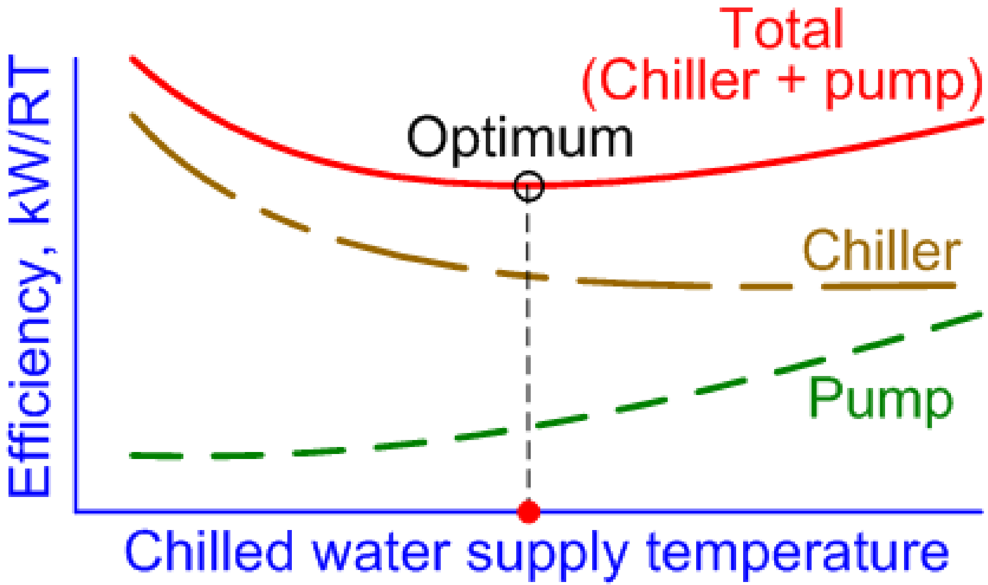
$= 53{,}550$ kWh/year

# Method of Chilled Water Supply Temperature Reset

**Chilled water supply temperature can be reset based on:**

- Position of the control valves on the cooling coils of AHU. Chilled water supply temperature can be reset upwards if control valve closes beyond the set value and vice versa
- Preset value of chilled water return temperature
- Cooling load or outdoor temperature

➢ When chilled water supply temperature is increased, the chilled water flow would have to be increased to satisfy the same cooling load for CAV systems resulting increase of pump power consumption



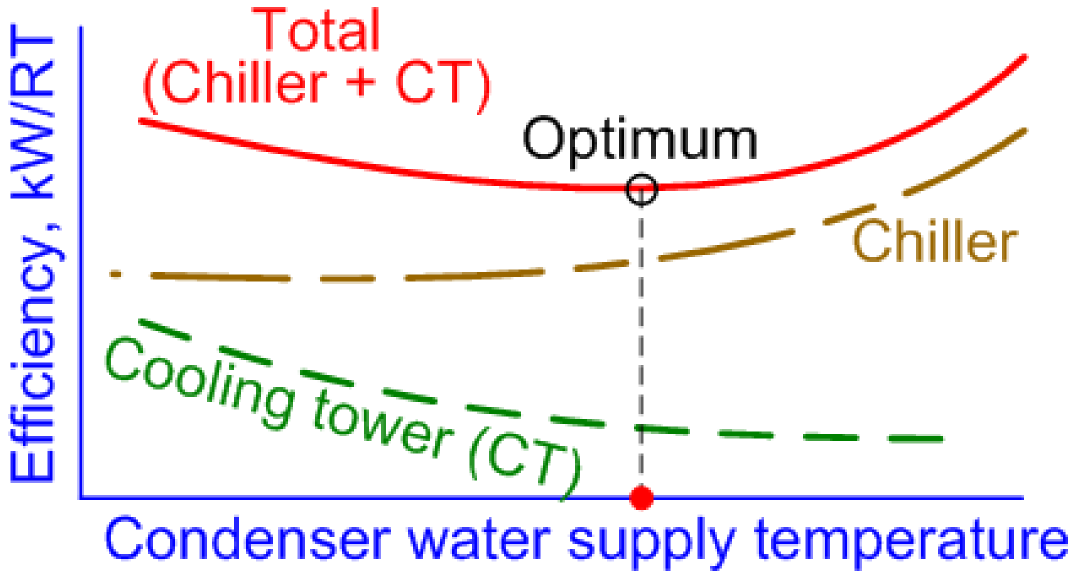

$$kW_{total} = kW_{compressor} + kW_{pump}$$

# Method of Condenser Water Supply Temperature Reset



- Same as chilled water temperature reset, for every 1°C reduction of condenser water temperature, chiller efficiency is improved by 2% to 3% due to the reduction of compressor lift and increase of cooling capacity.

- Lowering condenser water temperature results in higher cooling tower power consumption




$$kW_{total} = kW_{compressor} + kW_{cooling\ tower}$$

# Maintaining Surfaces of Condenser Water Tubes



- Scaling or fouling on the tube surface increases resistance to heat transfer in evaporator or condenser
- Condenser tubes are more prone to fouling since the circulating water is exposed to ambient air in cooling tower
- Research has shown that 0.6 mm of scale will increase chiller compressor power consumption by 20%

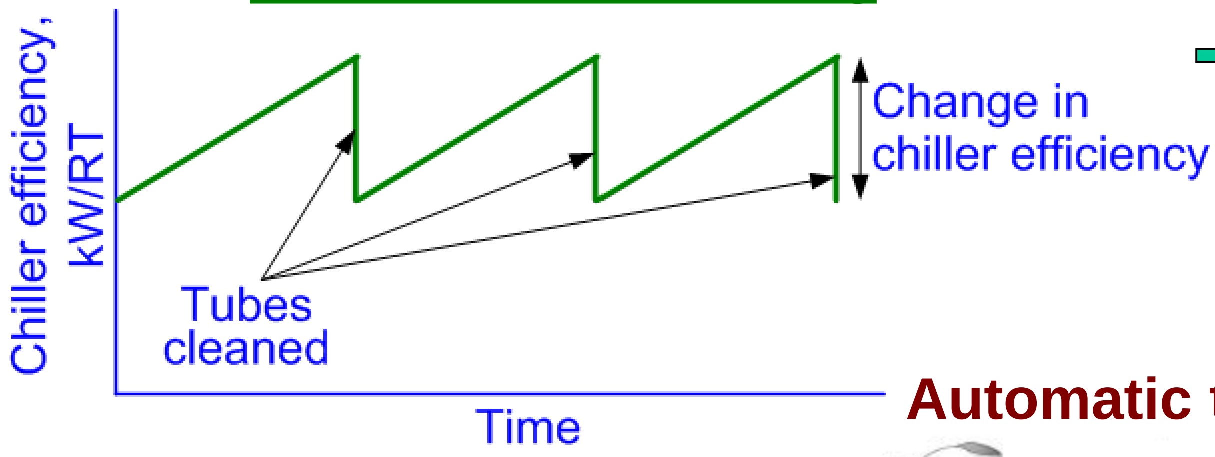
Scale and fouling in condenser is normally controlled by:

- Water treatment systems (increasing acidity)
- Water blow down
- Tube cleaning

# Maintaining Surfaces of Condenser Water Tubes



## Periodic tube cleaning

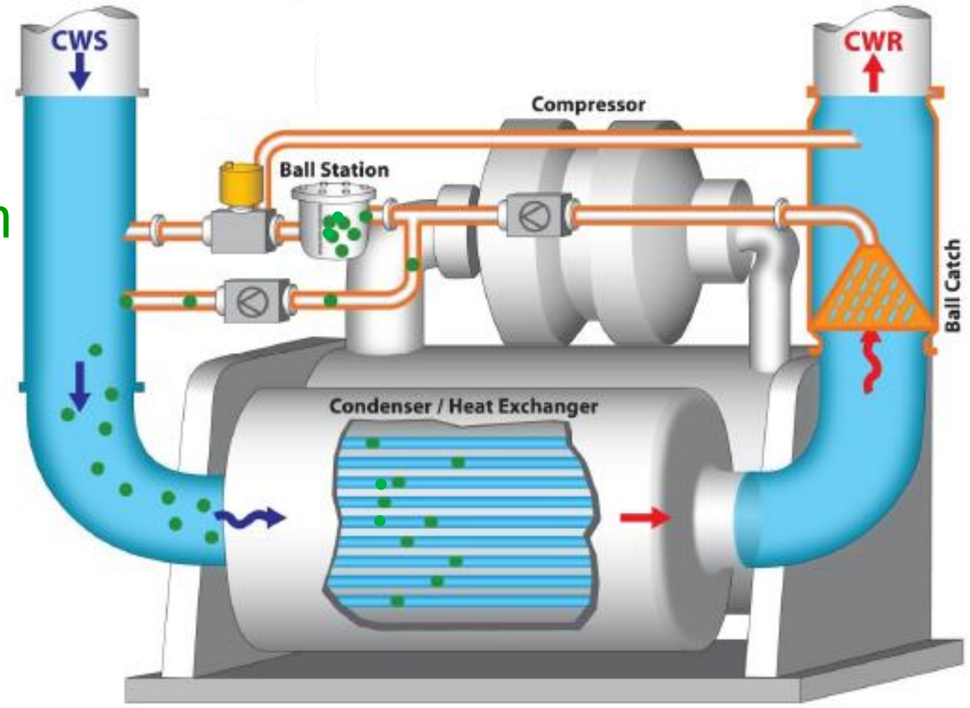



Chiller efficiency gradually drops again when scale and fouling builds up

## Automatic tube cleaning systems

- Ball & brush type
- Feasibility depends on condenser approach temperature

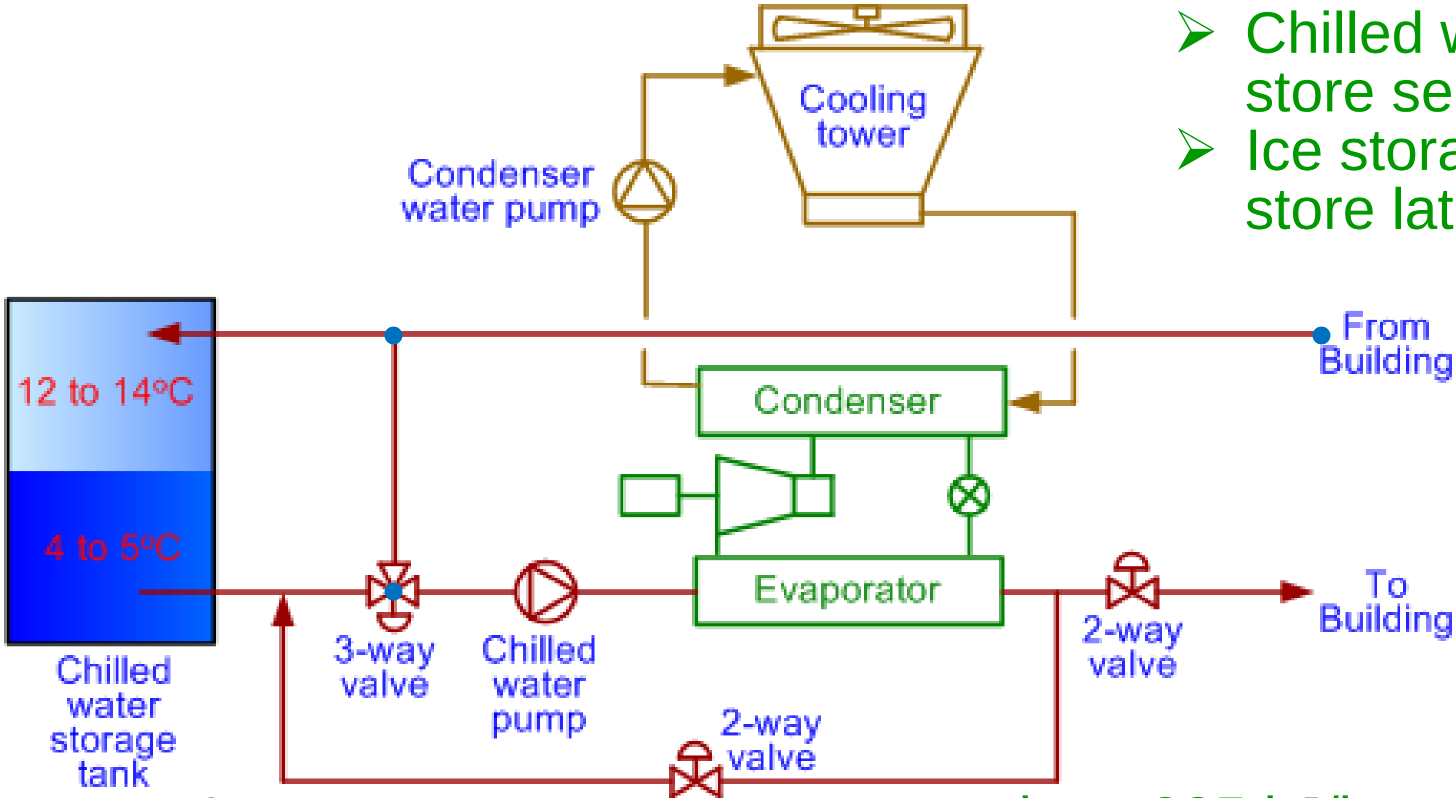
Sponge balls



# Thermal Energy Storage (TES) System



- Chilled water systems store sensible heat
- Ice storage systems store latent heat




- Ice storage system: can store about 335 kJ/kg
- Chilled water storage system: can store about 23 kJ/kg

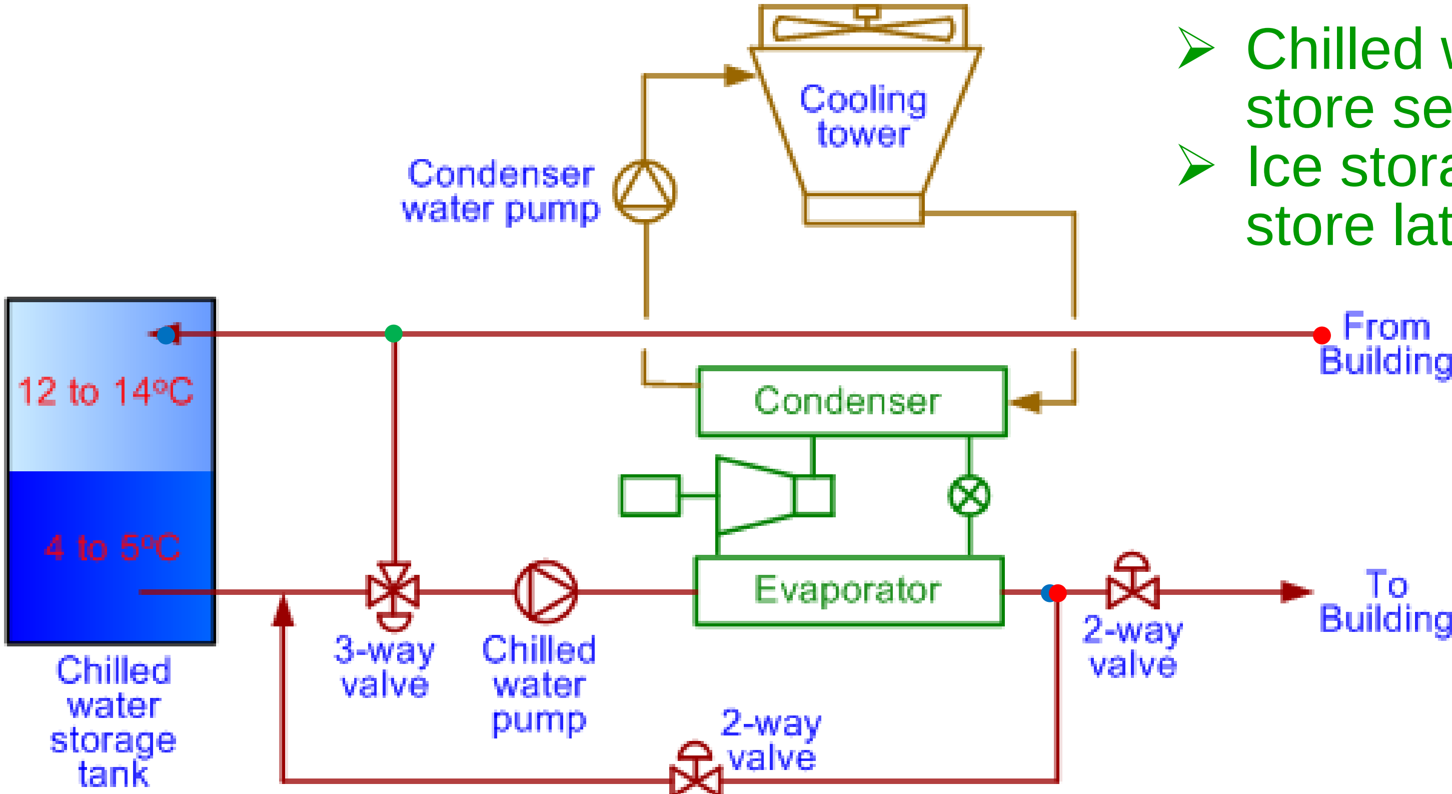
- Eutectic salts (inorganic salts & water) can be used in ice storage system to increase freezing point

Storage capacity is measured in RT-hours

- Chilled 500 RT-hours = 100 RT of cooling for 5 hours,
  Or, 250 RT of cooling for 2 hours

# Thermal Energy Storage (TES) System






- Chilled water systems store sensible heat
- Ice storage systems store latent heat

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• Chilled water storage system: can store about 23 kJ/kg

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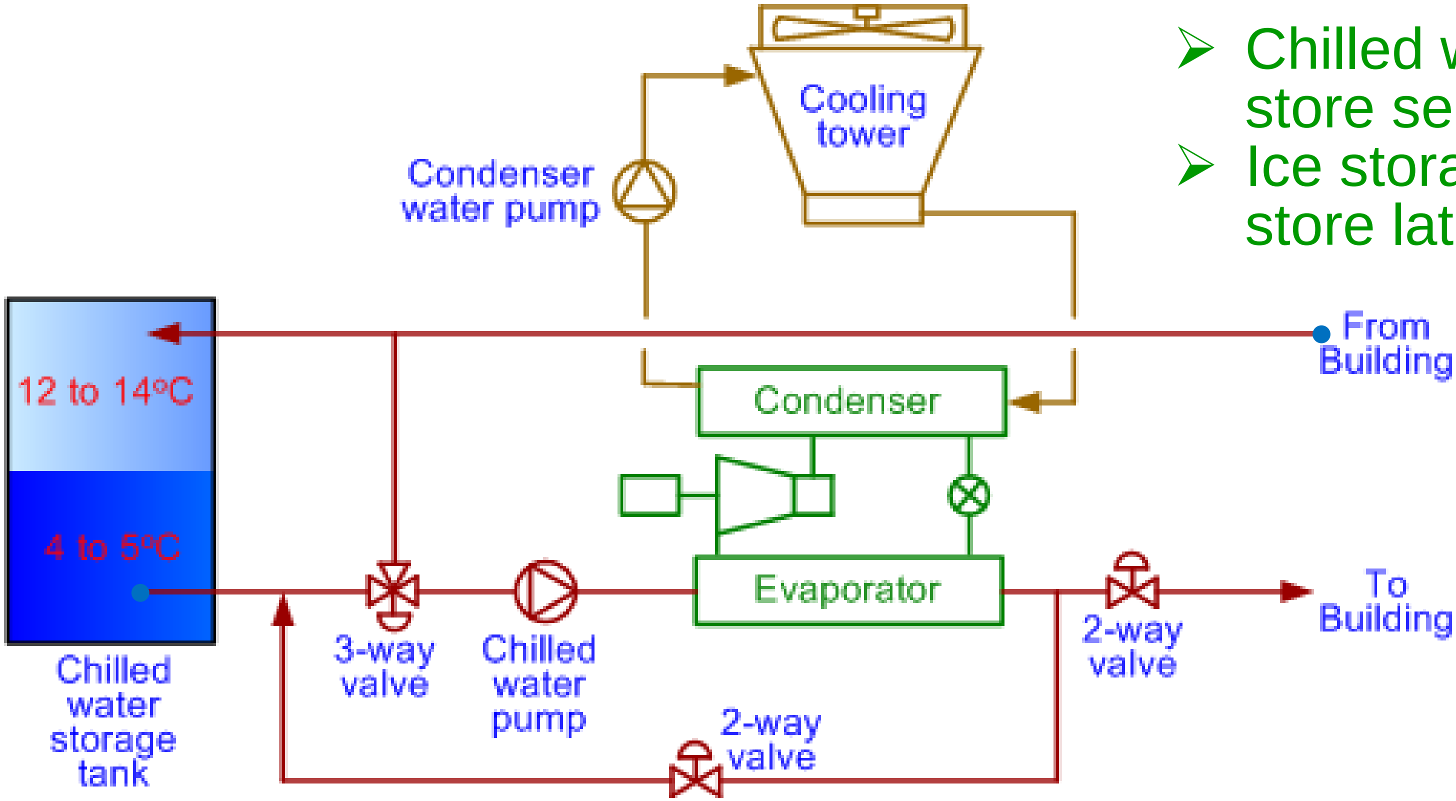
# Thermal Energy Storage (TES) System






- Chilled water systems store sensible heat
- Ice storage systems store latent heat

- Ice storage system: can store about 335 kJ/kg
- Chilled water storage system: can store about 23 kJ/kg

- Eutectic salts (inorganic salts & water) can be used in ice storage system to increase freezing point

Storage capacity is measured in RT-hours

- Chilled 500 RT-hours = 100 RT of cooling for 5 hours,
  Or, 250 RT of cooling for 2 hours

# Advantages of TES



**Reduce capital cost by:**

- Reducing cooling capacity of chiller system
- Reducing standby chiller and other equipment

**Reduce operating cost by:**

- Reducing maximum power demand for chiller system
- Making use of difference in peak & off-peak tariffs
- Improving chiller system efficiency during periods of low cooling demand

# Feasibility of TES



**Depends on**

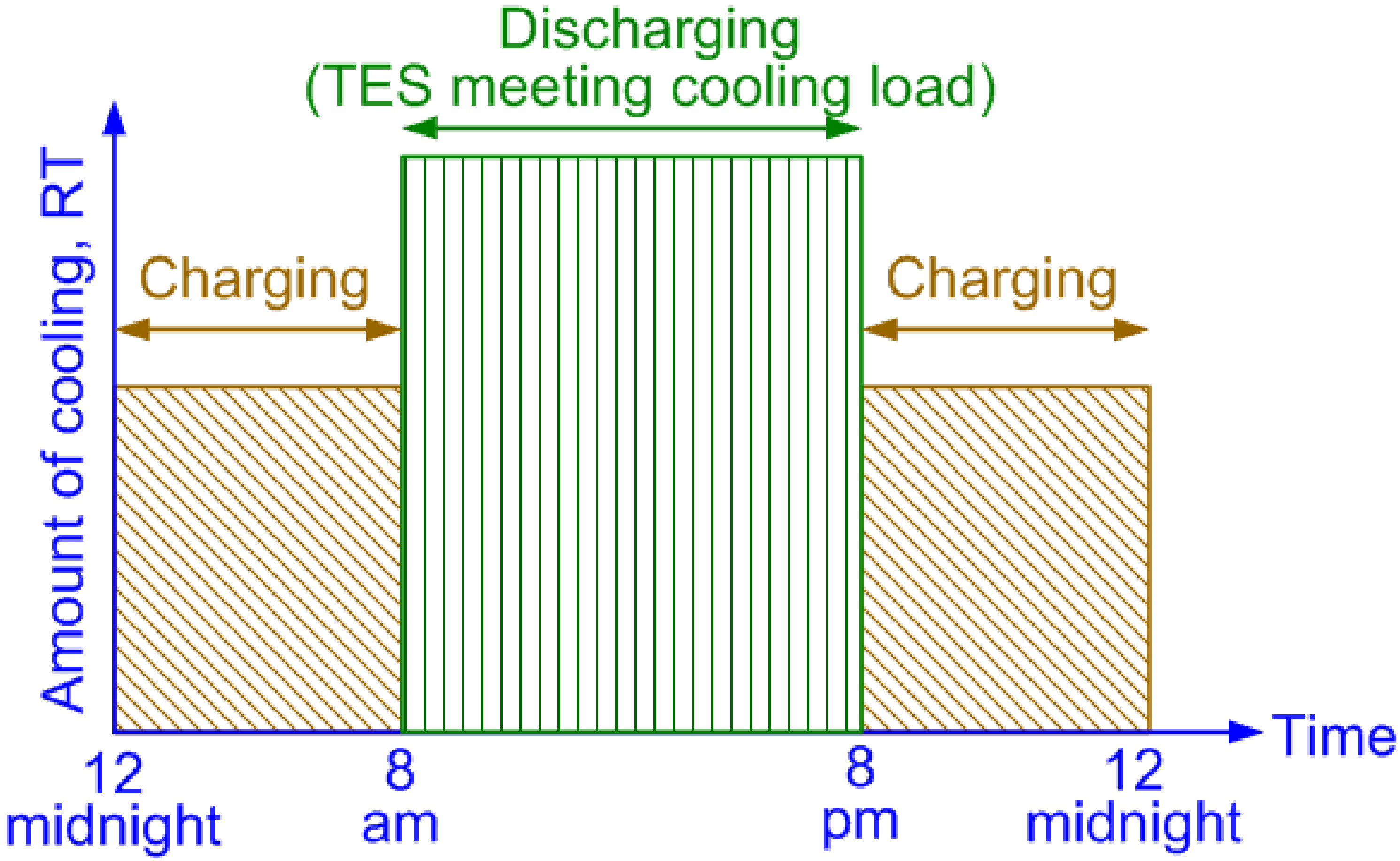
- **Cooling load profile**
  - Cooling load for short duration
  - Cooling loads occur infrequently

- **Electricity tariffs / availability**
  - Electricity cost is time dependent
  - High electricity demand charges
  - Electricity supply is limited

- **Others**
  - Interruption to cooling cannot be tolerated
  - Chiller system does not have spare peak capacity but has excess off-peak capacity
  - Tax rebates

# Full Storage Strategy

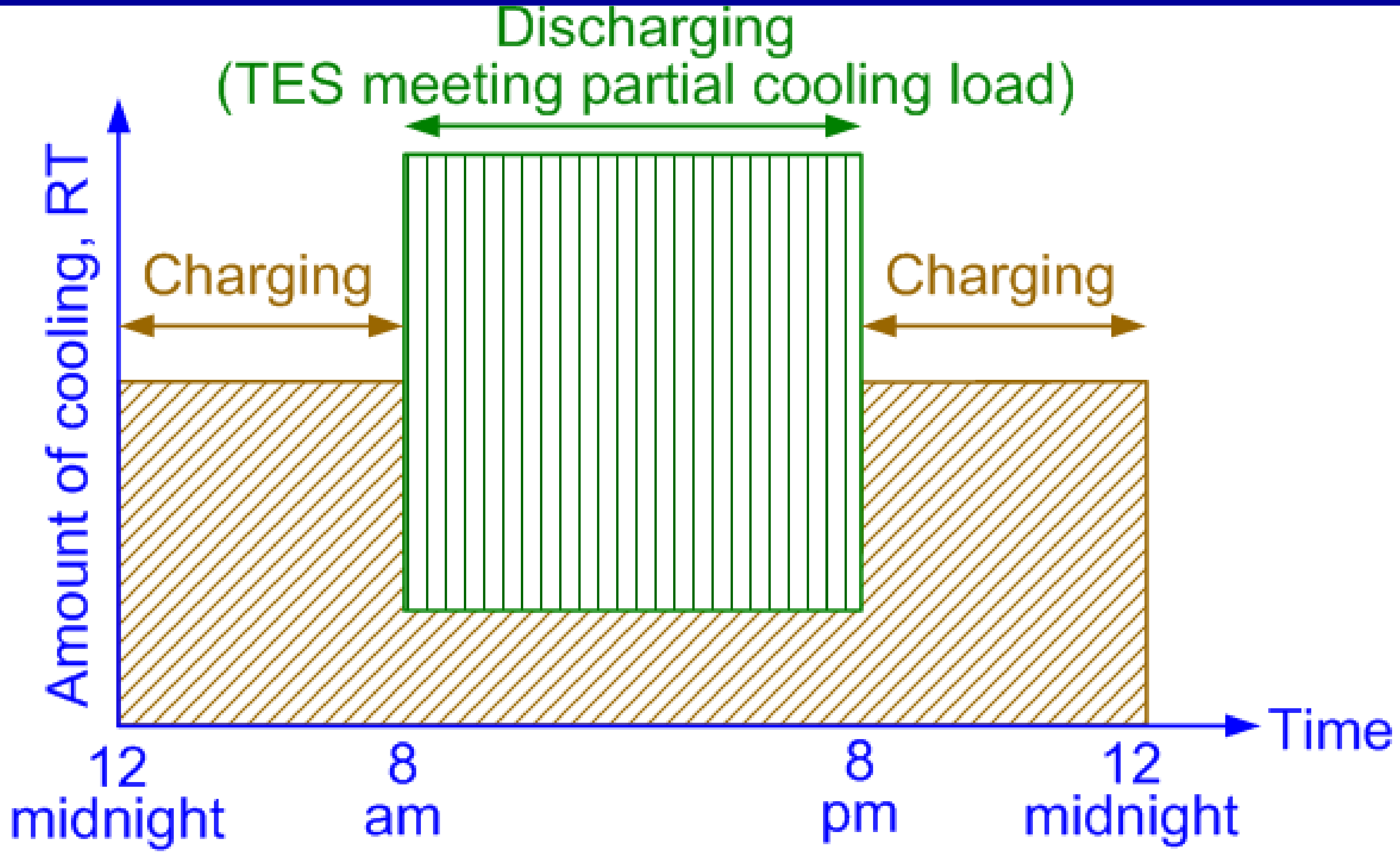





- Chiller system operates at full capacity during off-peak period and TES discharges during peak period
- Entire peak load is shifted to off-peak period

# Partial Storage Strategy






- Chiller system operates at peak period to meet only part of the cooling load
- TES is charged during off-peak period