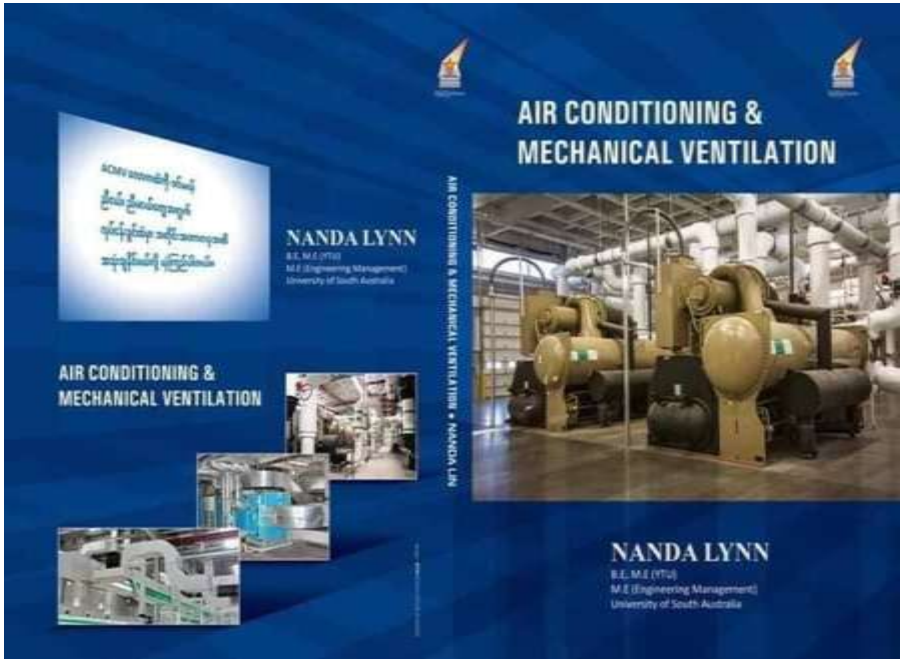
"Optimization of Chiller Efficiency"

NANDA LYNN
BE,M.E(YTU),
M.E(Engineering Management)
University of South Australia
26 January 2026

Air Conditioning & Mechanical Ventilation Book



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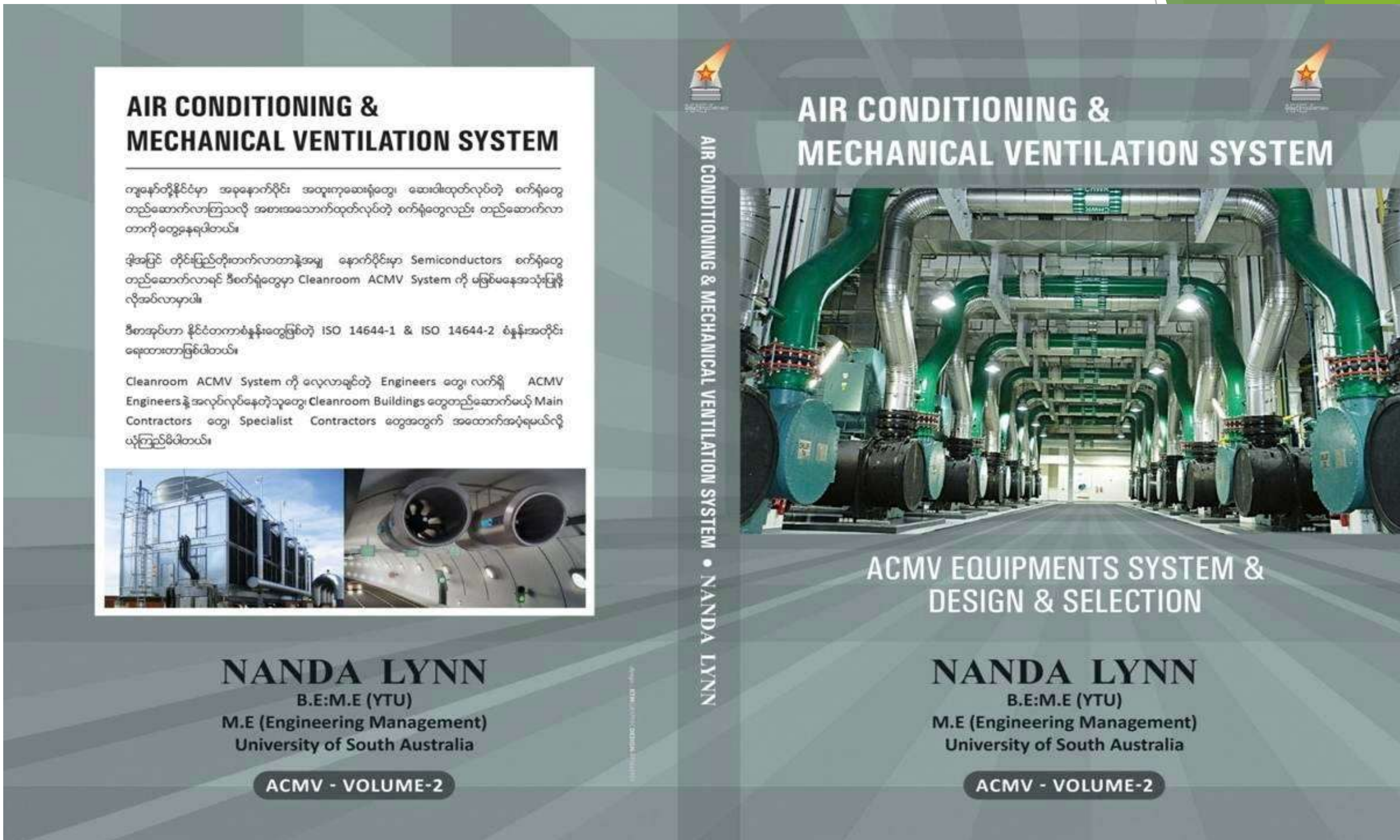

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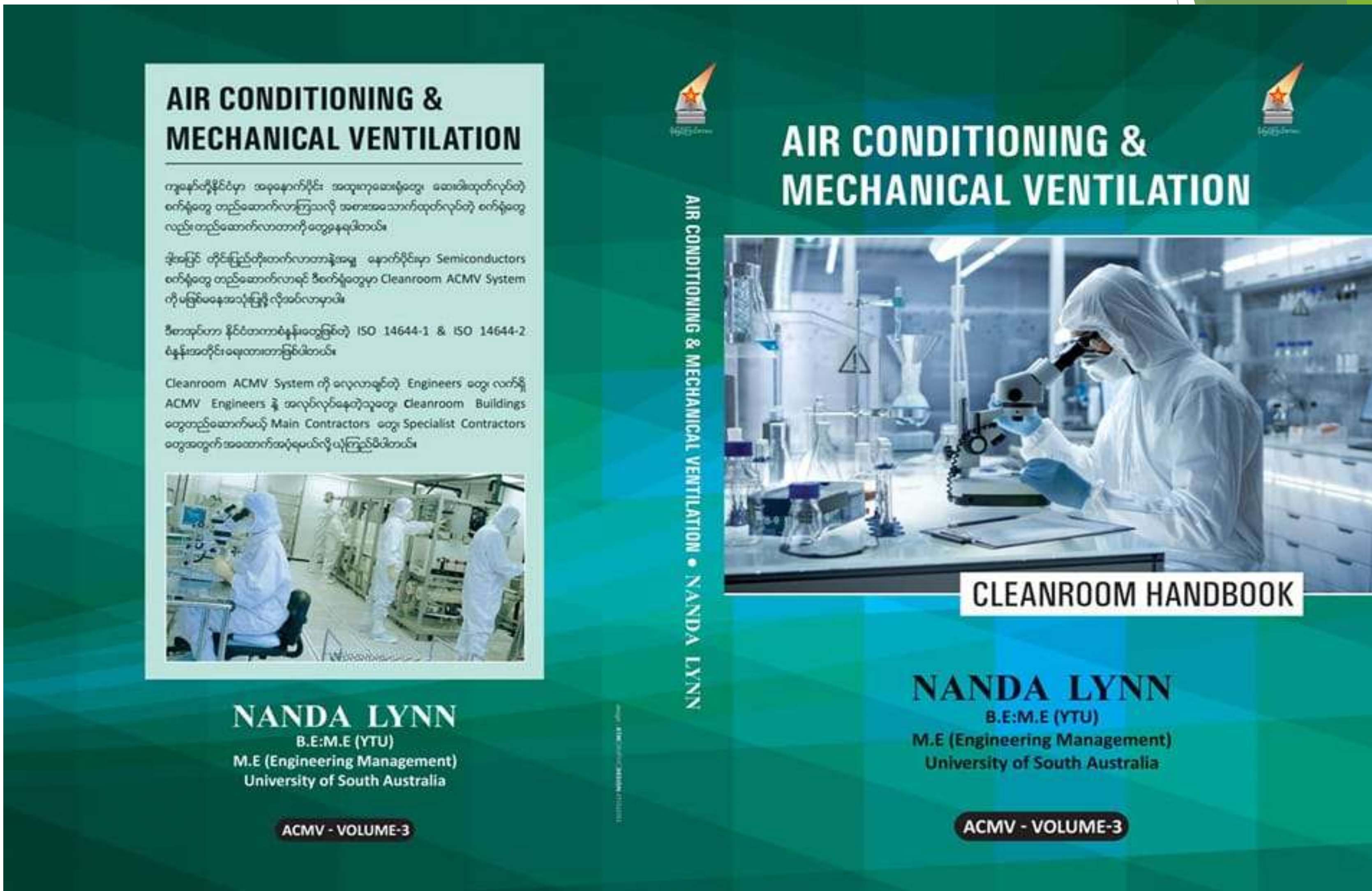

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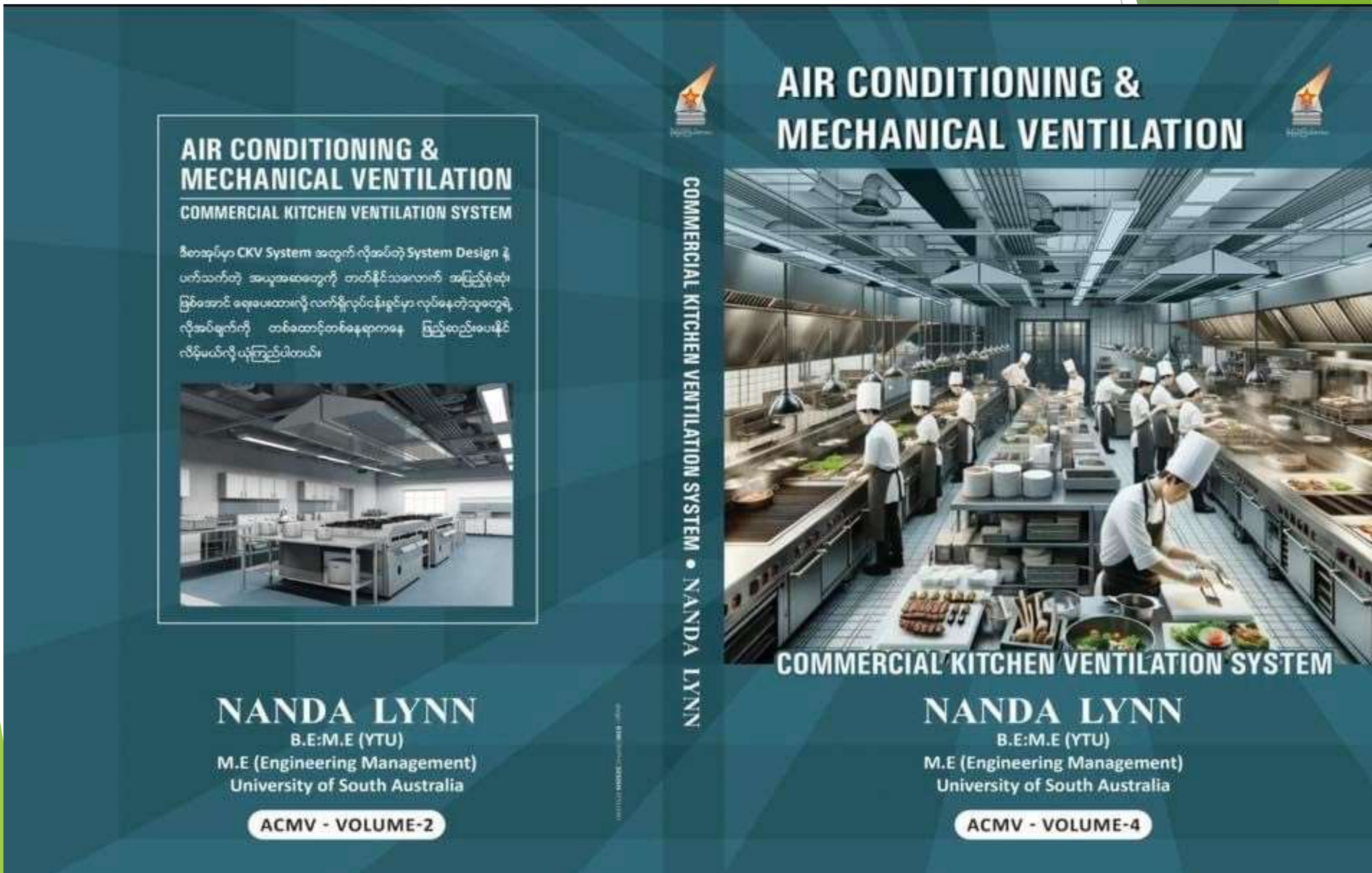

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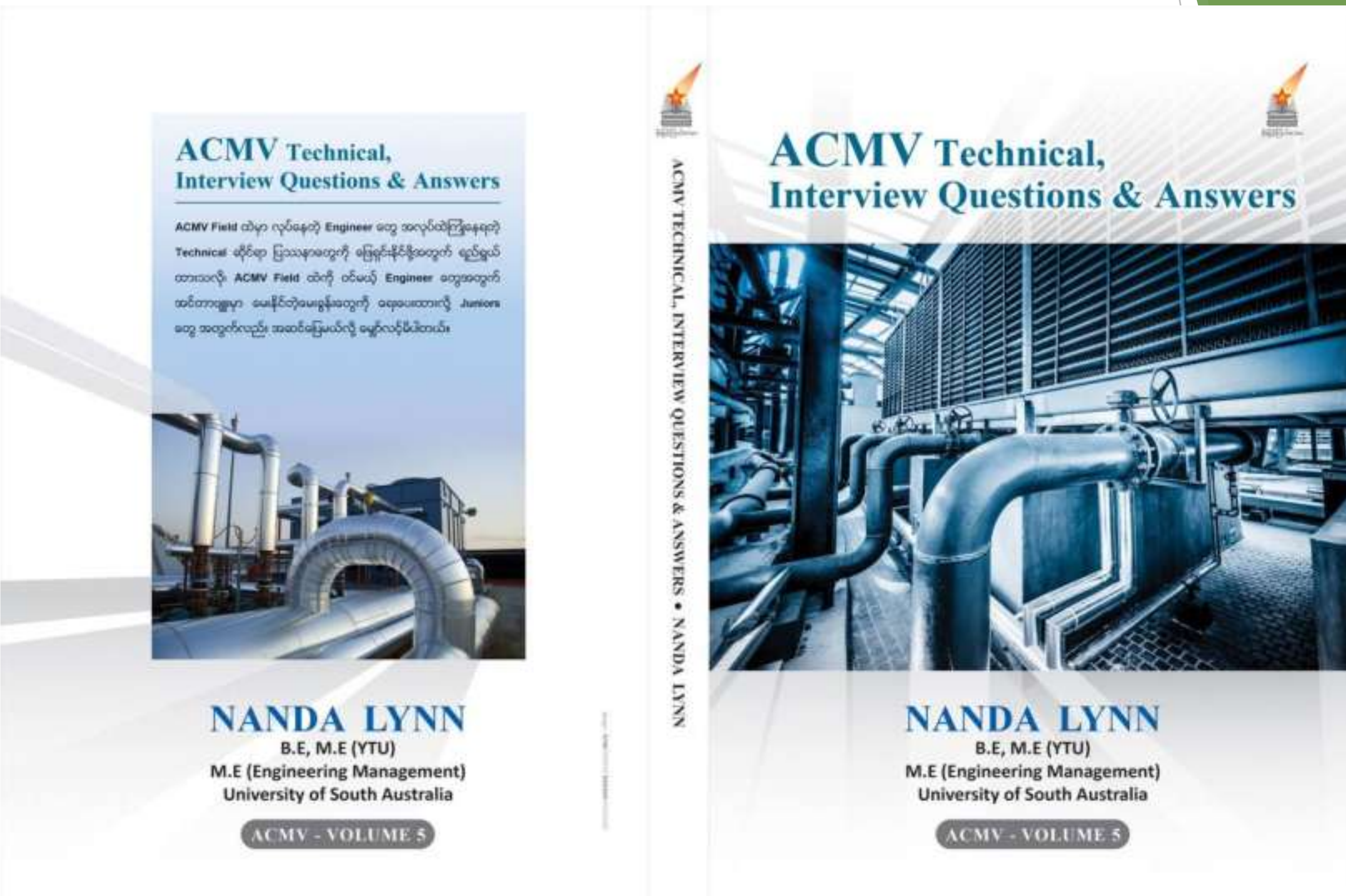

Air Conditioning Chilled Water System

- The purpose of ACMV system is to maintain the comfort condition in the air-conditioned space irrespective of the outdoor ambient condition.

- Comfort condition refers to a specific range of temperature, relative humidity, cleanliness and distribution of air to meet the comfort requirements of the occupants in air-conditioned spaces.

- For a tropical country, outdoor ambient temperature is generally higher than the comfort temperature of conditioned spaces.

- Central air conditioning plant is the single largest energy consumer that consumes about 60 % of the total energy consumption of a typical commercial building.

Vapor Compression Refrigeration Cycles

- Heat flows naturally from high temperature to low temperature spaces without requiring any devices.
- However, the reverse process of transferring heat from low temperature conditioned spaces to high temperature outdoor ambient air requires a special device called ACMV System.
- The air-conditioning machines, commonly known as chillers are cyclic devices.
- The working fluid used in the air conditioning cycle is called refrigerant.
- R123 & R134a are two commonly used in the air conditioning systems.

Vapour Compression Refrigeration Cycles

- Ozone depletion potentials (ODP) of R123 and R134a are 0.02 and 0 respectively.
- However, Global warming potential (GWP) of R123 and R134a are 77 and 1430 respectively.
- Based on Singapore Green Mark criteria, ODP of refrigerant should be or GWP should be less than 100.
- Both R123 and R134 a meet Singapore Green Mark Criteria.

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Vapour Compression Refrigeration Cycles

- The most frequently used air conditioning cycle is the vapour compression air conditioning cycle.
- This cycle consists of four main components :
- (a) Compressor
- (b) Condenser
- (c) Expansion valve and
- (e) Evaporator

Vapour Compression Refrigeration Cycles

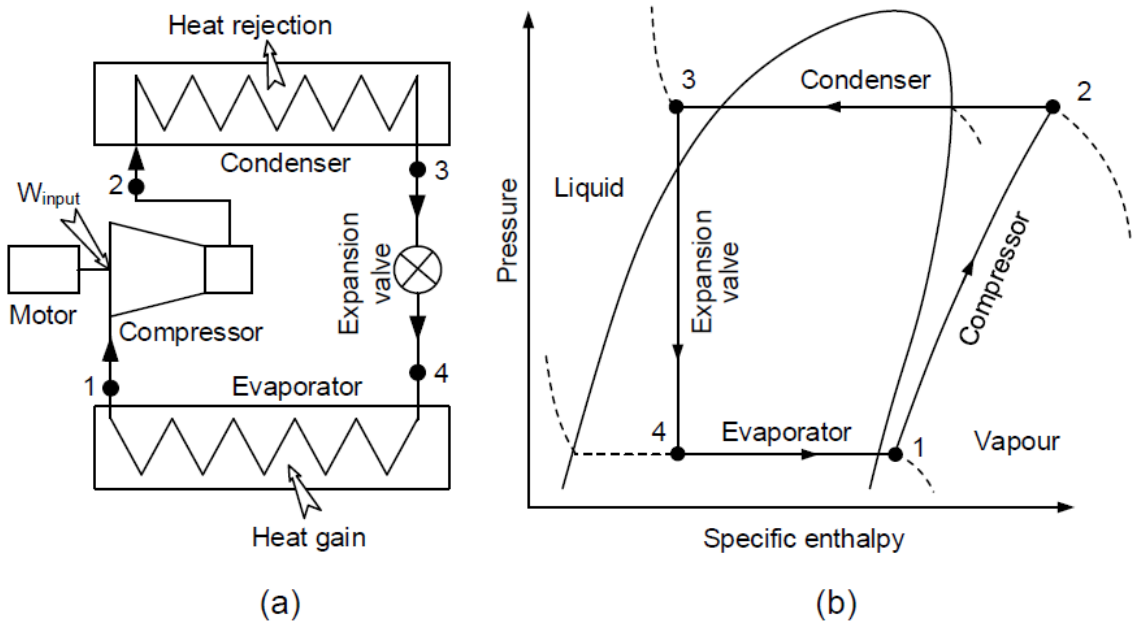


Figure 1.1 (a) Main components of air-conditioning system, (b) Pressure vs. specific enthalpy diagram

Function of Main Components

- 1) **Compressor:**
- The function of the compressor is to increase the pressure of refrigerant vapour from evaporator (point-1) to the condenser pressure (point-2).
- The compressor is driven by an electric motor using design gear box or transmission system.
- Compressor receives refrigerant as a saturated or slightly superheated vapour at low temperature and pressure (point-1) and discharges as superheated vapour at relatively high pressure and temperature (point-2)

Function of Main Components

- 1) **Condenser**

- The condenser is a heat exchanger. The function of the condenser is to reject heat from the refrigerant vapour to the surrounding ambient air or the cooling water known as condenser water.

- Superheated refrigerant vapour of relatively high pressure and temperature (point-2) enters the condenser, rejects latent heat of condensation and leaves as saturated or slightly subcooled liquid refrigerant of high pressure and temperature (point-3)

Function of Main Components

- 1) **Expansion Valve**

- The function of expansion valve is to reduce the pressure of liquid refrigerant from the condenser pressure (point-3) to the evaporator pressure (point-4).

- Boiling temperature of liquid refrigerant drops due to the reduction of refrigerant pressure after the expansion valve (point-4).

- Low pressure liquid refrigerant partly evaporates by absorbing latent heat of vaporization from the liquid refrigerant itself and enters the evaporator as a liquid mixture (point-4) of low pressure and temperature.

Function of Main Components

- 1) <u>Evaporator</u>

- The evaporator is also a heat exchanger. In the evaporator, the liquid refrigerant absorbs heat from the surrounding air or circulating water known as chilled water.

- Partially evaporated liquid vapour mixture of refrigerant of low pressure and temperature (point-4) enters the evaporator, absorbs latent heat of vapourisation from the surrounding air or chilled water and then leaves as saturated or slightly superheated refrigerant vapour of low pressure and temperature (point-1)

- Low pressure liquid refrigerant partly evaporates by absorbing latent heat of vaporization from the liquid refrigerant itself and enters the evaporator as a liquid mixture (point-4) of low pressure and temperature.

Types of Air Conditioning Systems

- Air conditioning systems are broadly classified as
- (a) Vapour compression type and
- (b) Vapour absorption type

- **Vapour compression type air conditioning system**

- The compressor is the biggest energy consuming component of vapour compression type air conditioning systems.

- Vapour compression types systems are classified according to the types of compressors used for the compression of the refrigerant.

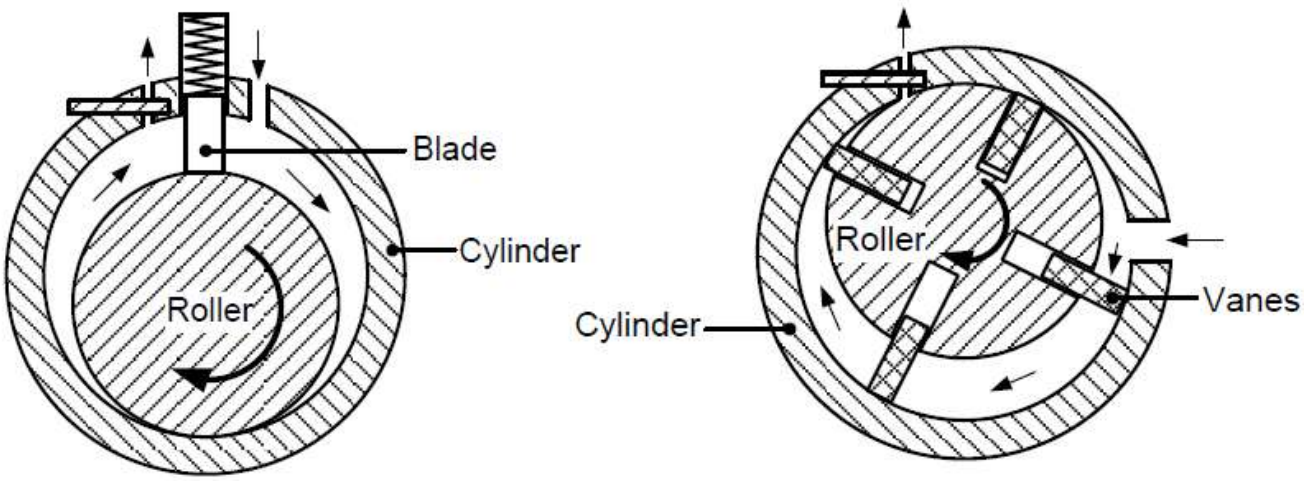
Types of Air Conditioning Systems

- The common types of compressor used in the chillers are:
- (i) Rotary compressor
- (ii) Reciprocating compressor
- (iii) Scroll compressor
- (iv) Screw compressor
- (v) Centrifugal compressor

- **(i) Rotary Compressor**
- Rotary compressor belong to the positive displacement type, and there are mainly two designs for the rotary compressors are

- (a) Rolling piston type and
- (b) Rotating vane type

Types of Air Conditioning Systems



(a) Rolling piston type compressor

(b) Rotating vane type compressor

Figure 1.2 Rotary compressor

Types of Air Conditioning Systems

- **(ii) Reciprocating Compressor**

- Main Components of reciprocating compressors are cylinder, piston, connecting rod, crank shaft, motor and valves.

- The crank shaft is driven by a motor and rotational motion of crank shaft is converted to reciprocation motion of the piston using a connecting rod.

- Reciprocation compressors are typically used for low capacity applications up to about 100 RT (350 kw).

- Multiple compressors are used for high capacity application.

Reciprocation Compressor

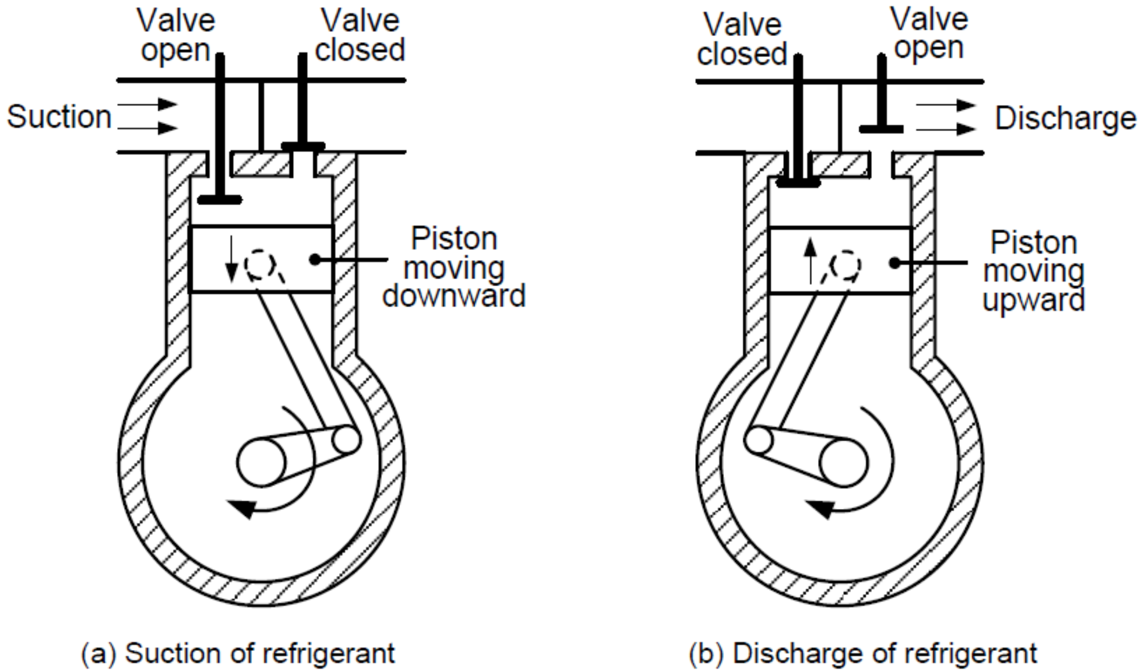


Figure 1.3 Reciprocating compressor

Types of Air Conditioning Systems

- **(ii) Scroll Compressor**

- Scroll compressors contain two spiral-shaped scroll members which are interfitted .

- One scroll remains stationary while the other rotates eccentrically.

- Due to the eccentric motion and profile of the scrolls, refrigerant drawn in through the inlet opening is compressed between the scrolls during the rotation and then discharged as the outlet port.

- Scroll compressors belong to the positive displacement type.

- Scroll compressors are typically used for low capacity applications up to about 20 RT (70 kW).

Scroll Compressor

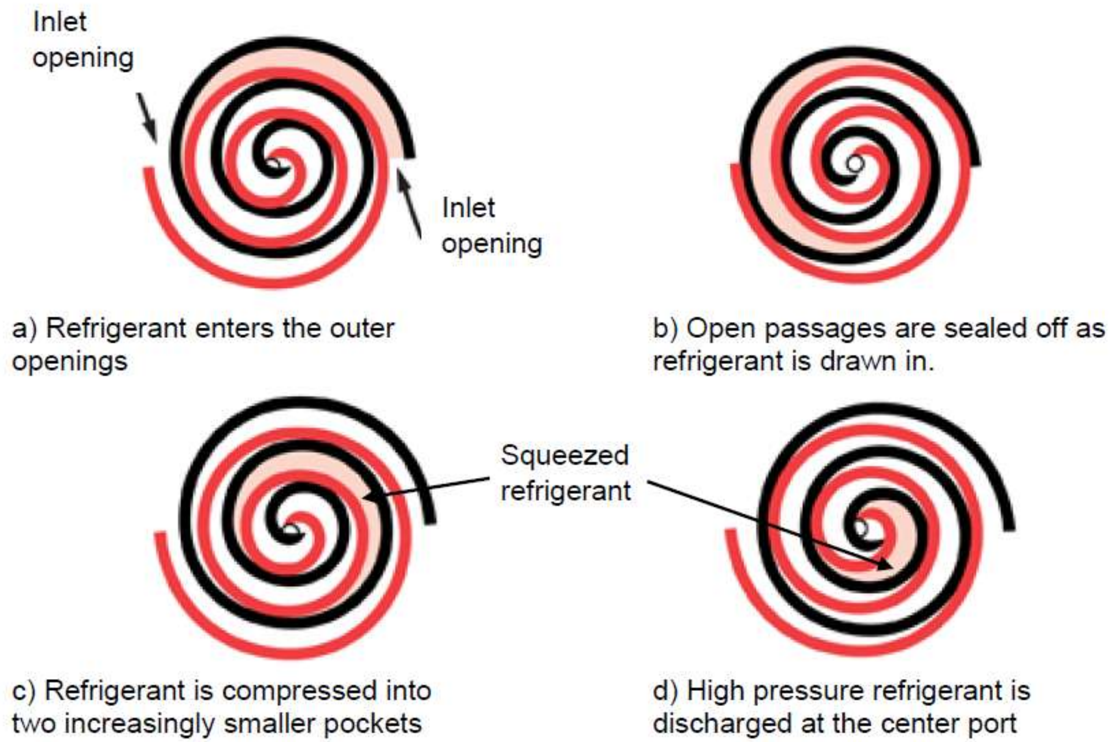


Figure 1.4 Compression process of scroll compressor

Types of Air Conditioning Systems

- **(ii) Screw Compressor**

- Screw compressors contain a set of male and female helically grooved rotors.

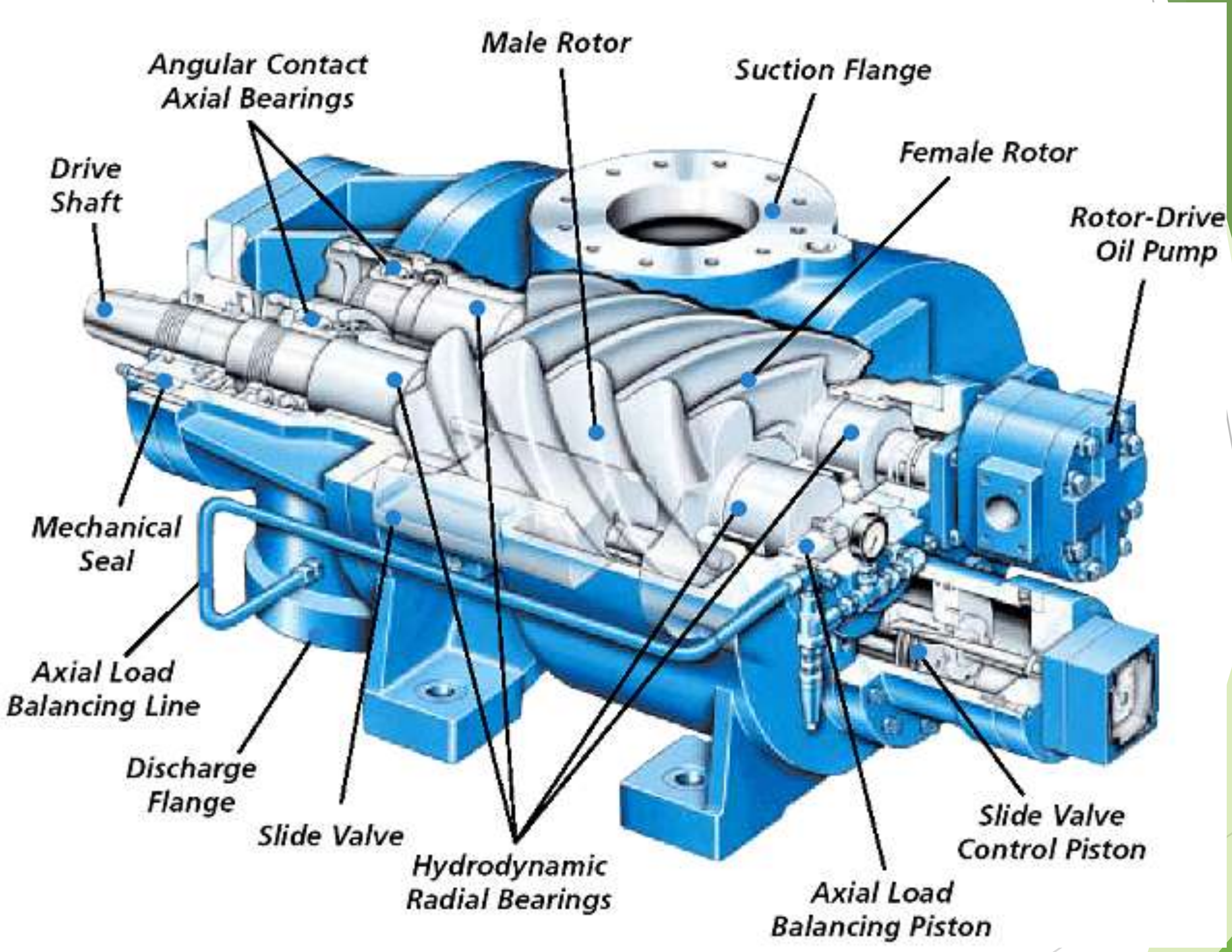
- The male rotor is generally connected with the motor and functions as the driving rotor.

- The other female rotor generally functions as the driven rotor.

- Screw compressors belong to the positive displacement type.

- Screw compressors are typically used for medium capacity applications up to about 600 RT (2,110 kW).

Types of Air Conditioning Systems



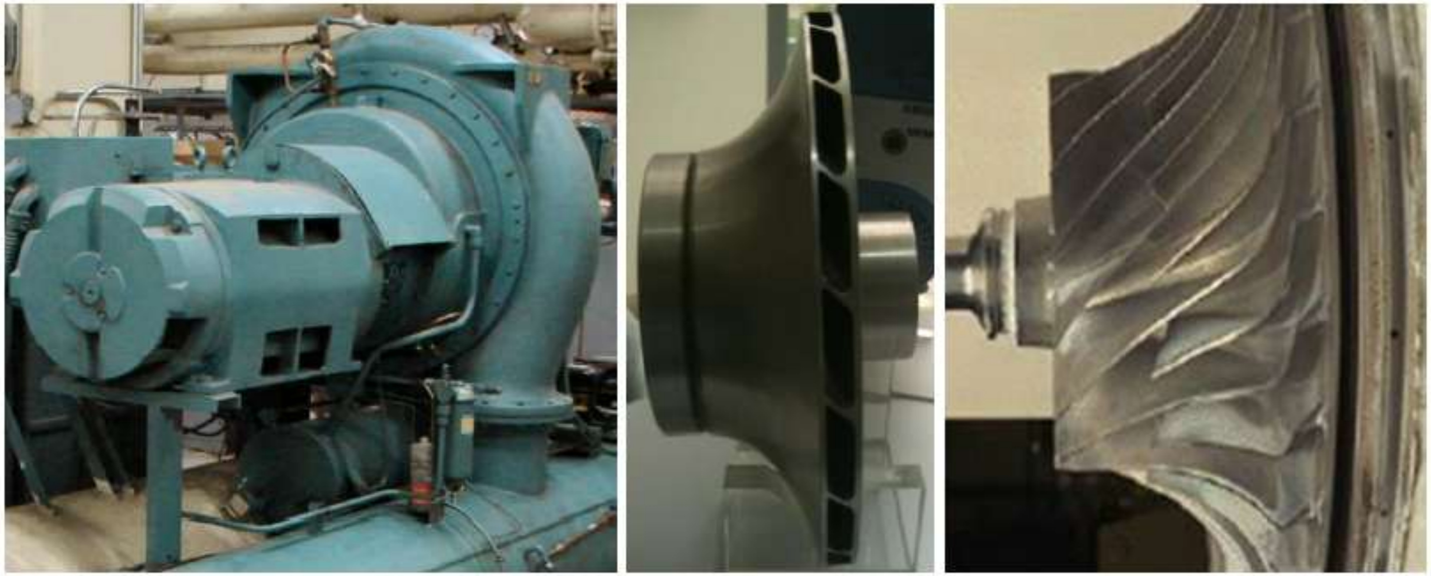
Types of Air Conditioning Systems

Figure 1.5 Sectional view of screw compressor

Types of Air Conditioning Systems

- **(ii) Centrifugal Compressor**
- Centrifugal compressor consist of impeller housed inside a volute casing.
- The impeller is mounted on a shaft and rotates at high speed
- Refrigerant enters the impeller in the axial direction and is discharged radially at high velocity.
- The kinetic energy of the refrigerant is converted to static pressure in the diffuser.
- Centrifugal compressors are typically used for high capacity applications usually above 300 RT 1,055 kW).

Types of Air Conditioning Systems



(a) Assembly of centrifugal compressor (b) Two different designs of impeller

Figure 1.6 Centrifugal compressor

Components and Layouts of Central Chilled Water System

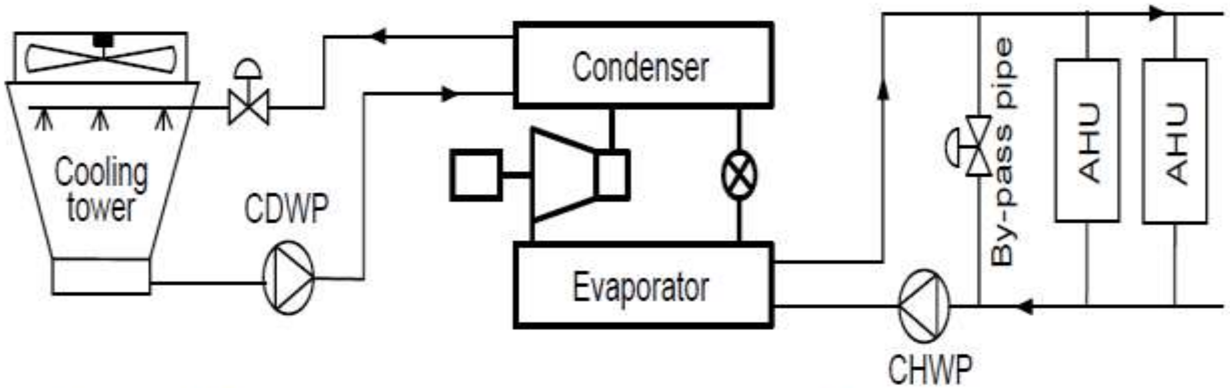


Figure 1.10 Main components of water-cooled central air-conditioning system

Components and Layouts of Central Chilled Water System

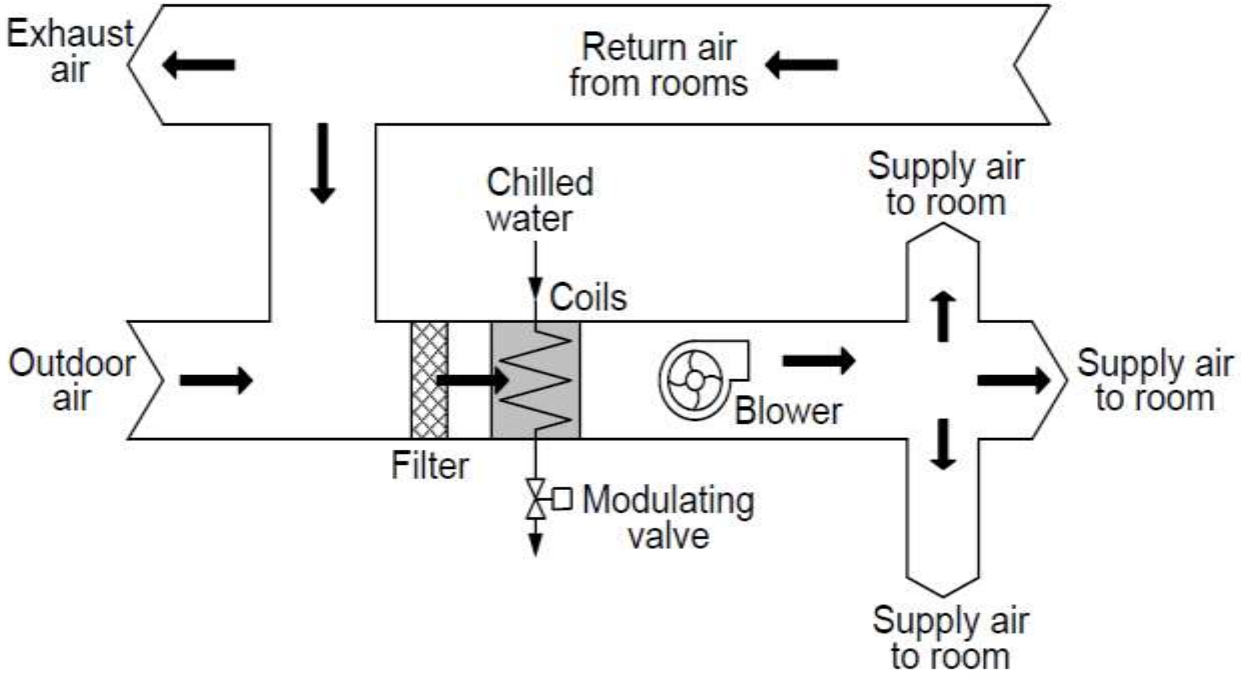


Figure 1.11 Main components of a typical air handling unit (AHU)

Components and Layouts of Central Chilled Water System

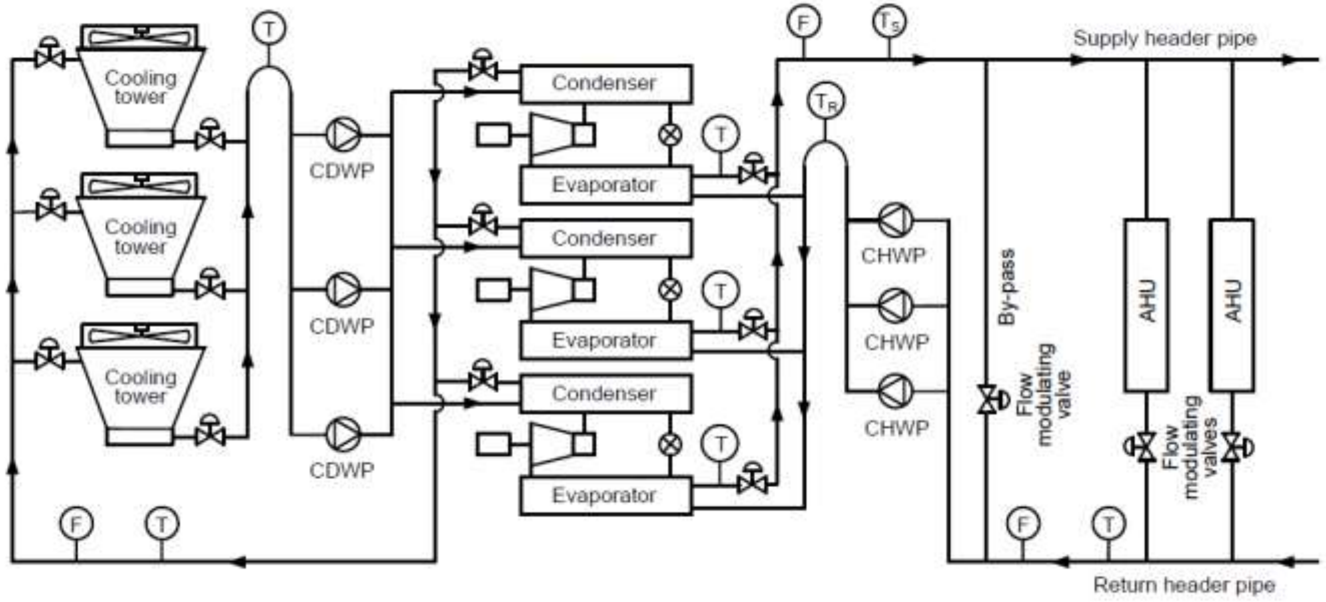


Figure 1.12 Central air-conditioning plant with primary chilled water pumping system. CHWP: Chilled water pump; CDWP: Condenser water pump; T: Temperature sensor; F: Flow meter.

Components and Layouts of Central Chilled Water System

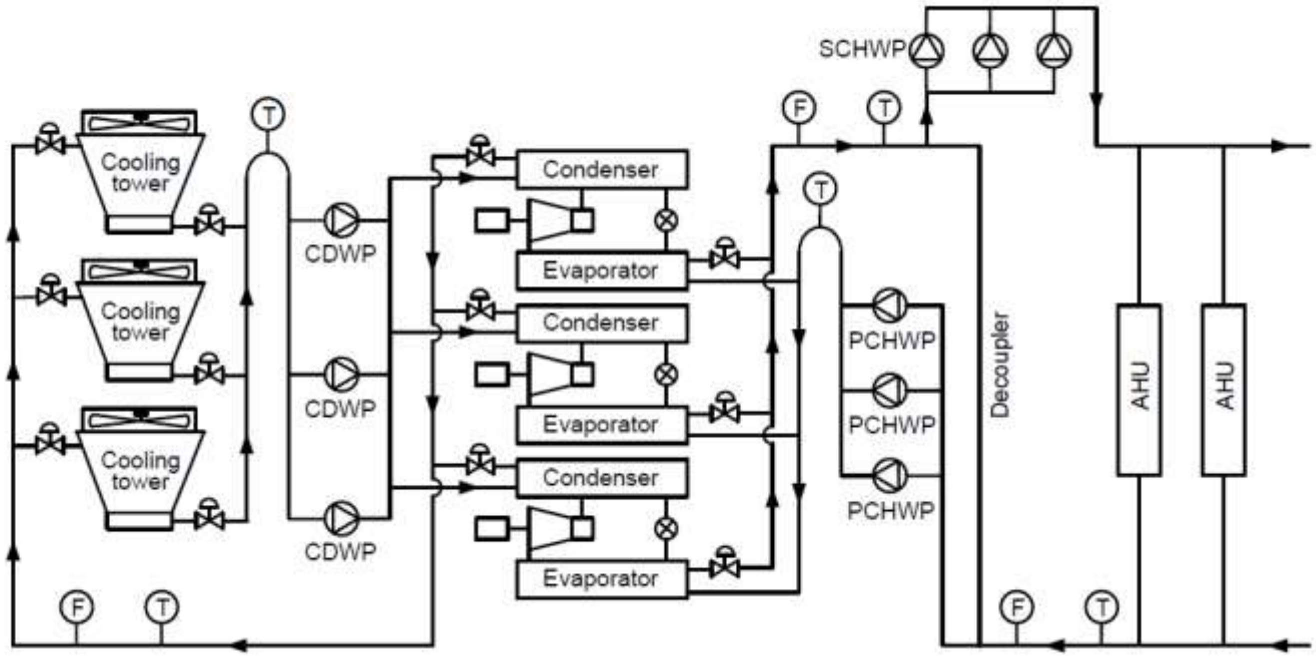


Figure 1.13 Central air-conditioning plant with primary and secondary chilled water pumping system. PCHWP: Primary chilled water pump; SCHWP: Secondary chilled water pump; CDWP: Condenser water pump; T: Temperature sensor; F: Flow meter.

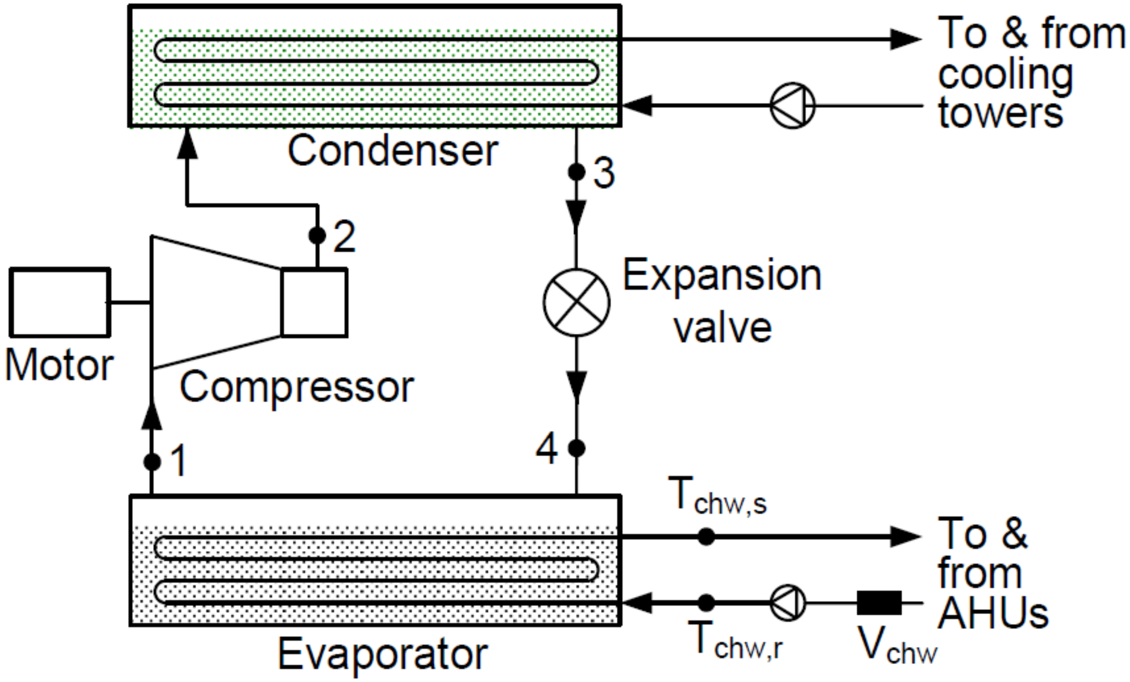


Figure 1.14 Location of sensors for measuring chiller cooling load

$$Q_{ev} = m_{r,1}(h_{r,1} - h_{r,4})$$

where,

Q_{ev} = Cooling load for chiller or rate of heat gain in evaporator, kW

$m_{r,1}$ = Mass flow rate of refrigerant at point-1, kg/s

$h_{r,1}$ = Specific enthalpy of refrigerant at point-1, kJ/kg

$h_{r,4}$ = Specific enthalpy of refrigerant at point-4, kJ/kg

Measurement and Calculation of Chilled Water System Performance

$$Q_{ev} = V_{chw}\rho_{chw}C_p\left(T_{chw,r} - T_{chw,s}\right)$$

where

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

ρ_{chw} = Chilled water density, kg/m^3

C_p = Specific heat of chilled water, kJ/kg. K

$T_{chw,r}$ = Chilled water return temp, °C

$T_{chw,s}$ = Chilled water supply temp, °C

Q_{ev} = Cooling load for chiller or the rate of heat gain in evaporator, kW

$$Q_{ev} = V_{chw}\left(T_{chw,r} - T_{chw,s}\right)/13.3$$

where

V_{chw} = Chilled water flow rate, GPM

$T_{chw,r}$ = Chilled water return temp, °C

$T_{chw,s}$ = Chilled water supply temp, °C

Q_{ev} = Cooling load for chiller or the rate of heat gain in evaporator, RT

Calculation of Heat Rejection Rate by Condenser

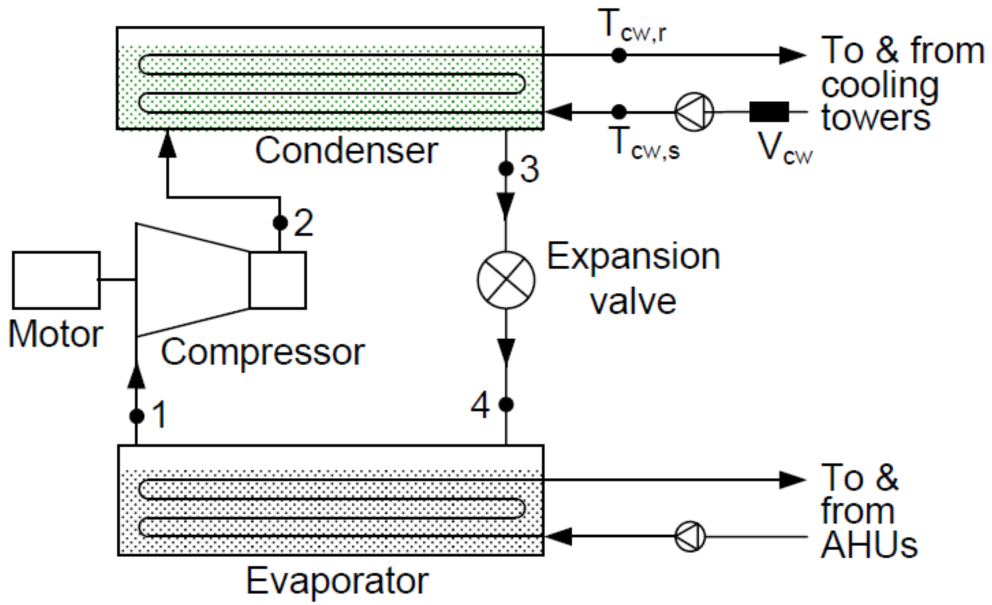


Figure 1.15 Location of sensors for measuring heat rejection rate of condenser

$$Q_{cd} = m_{r,3}\left(h_{r,2} - h_{r,3}\right)$$

where,

Q_{cd} = Heat rejection rate from condenser, kW

$m_{r,3}$ = Mass flow rate of refrigerant at point-3, kg/s

$h_{r,2}$ = Specific enthalpy of refrigerant at point-2, kJ/kg

$h_{r,3}$ = Specific enthalpy of refrigerant at point-3, kJ/kg

Heat Rejection rate from condenser can be calculated as:

$$Q_{cd} = V_{cw}\rho_{cw}C_p\left(T_{cw,r} - T_{cw,s}\right)$$

where

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

ρ_{cw} = Condenser water density, kg/m^3

C_p = Specific heat of condenser water, kJ/kg. K

$T_{cw,r}$ = Condenser water return temp, °C

$T_{cw,s}$ = Condenser water supply temp, °C

Q_{cd} = Heat rejection rate from condenser, kW

$$Q_{cd} = V_{cw}\left(T_{cw,r} - T_{cw,s}\right)/13.3$$

where

V_{cw} = Condenser water flow rate, GPM

$T_{cw,r}$ = Condenser water return temp, °C

$T_{cw,s}$ = Condenser water supply temp, °C

Q_{cd} = Heat rejection rate from condenser, RT

Energy Balance Equation for Chiller

$$Q_{ev} + W_{input} = Q_{cd} \quad (1.7)$$

where

Q_{ev} = Heat gain in evaporator, kW

W_{input} = Electrical power input to the compressor, kW

Q_{cd} = Heat rejection rate by the condenser, kW

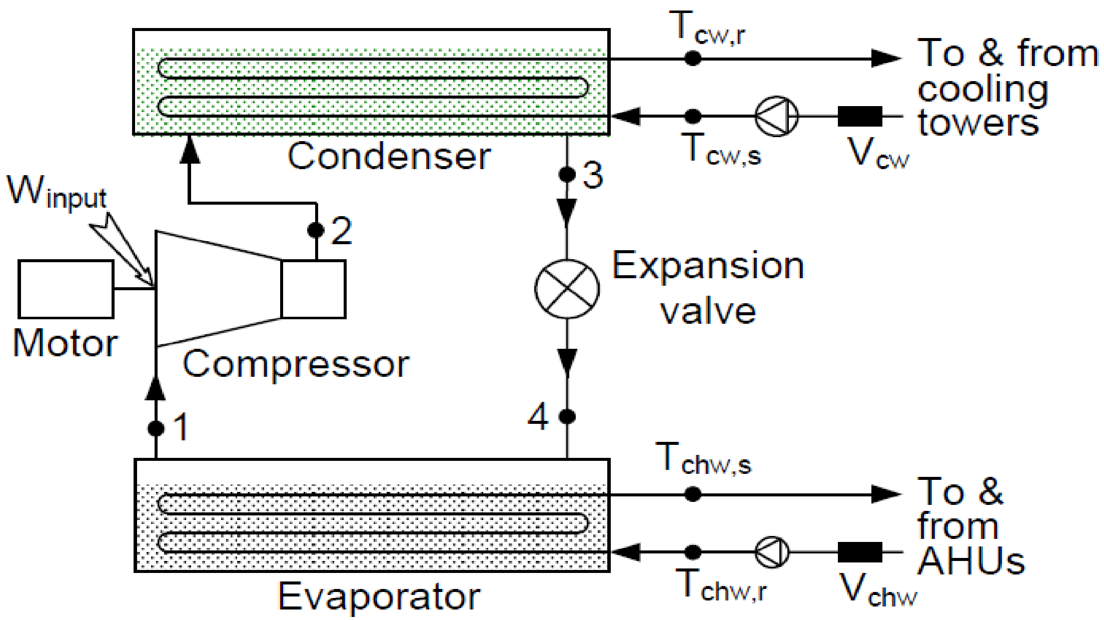


Figure 1.16 Location of sensors for measuring the chiller cooling load and heat rejection rate of condenser

Energy Balance Equation for Chiller

$$W_{input} = m_{r,1}(h_{r,2} - h_{r,1})$$

where,

W_{input} = Input power to the compressor, kW

$m_{r,1}$ = Mass flow rate of refrigerant at point-1, kg/s

$h_{r,1}$ = Specific enthalpy of refrigerant at point-1, kJ/kg

$h_{r,2}$ = Specific enthalpy of refrigerant at point-2, kJ/kg

Motor & Compressor Coupling

- Type-1 : Open-Type Compressor with Prime Move and External Gear Drive
- In open-type compressors, the motor is mounted externally and cooled by the surrounding air.

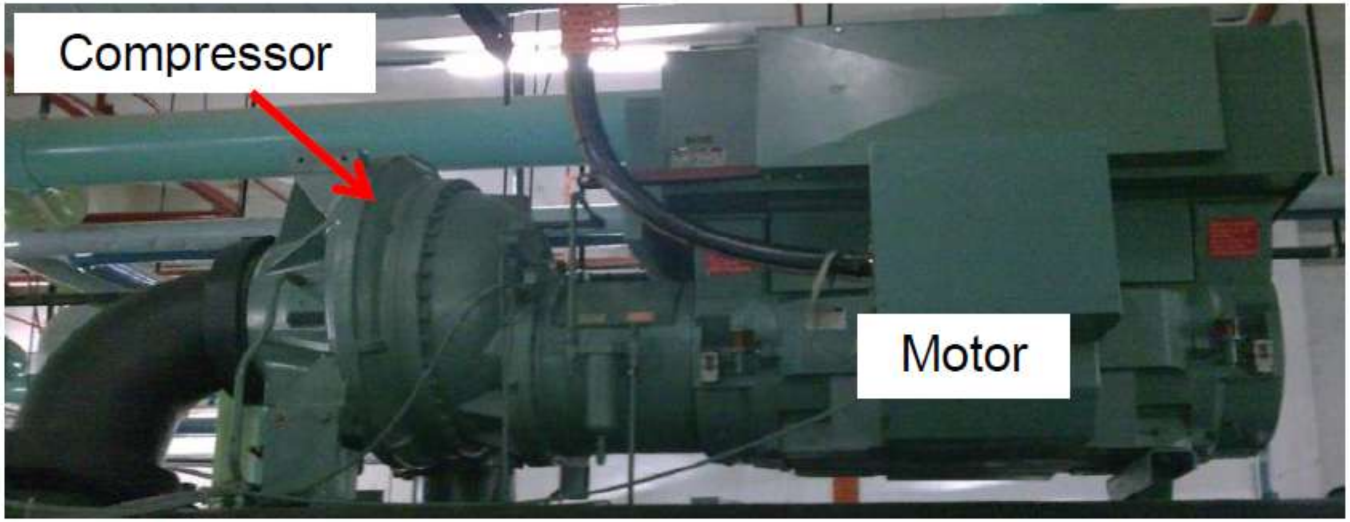


Figure 1.17 Photograph of an open-type compressor system

Type-2 Open-Type Compressor with Direct Drive

- If the motor is directly coupled with the compressor, the efficiency of the direct drive is usually considered as 100 % (no loss).

Type-3 Hermetically Sealed Compressor

- Hermetically sealed compressors have their motor enclosed along with compressor inside a dome.
- The motor is cooled by the incoming suction vapour of refrigerant.
- They have advantages of less noise and no refrigerant leakage

Figure : Hermetically Sealed Compressor

Calculation of Chiller Efficiency

- Chiller efficiency is defined as the magnitude of electric power consumed by the motor of compressor or chiller power consumption to produce one unit of cooling effect.
- (i) Chiller Efficiency in kW/RT = Electric power consumed by motor of compressor in kW/ Cooling effect produced in RT

- Chiller Efficiency = $\dfrac{\text{Chiller power consumption , kW}}{\text{Chiller Cooling Load , RT}}$

Chiller Efficiency is also expressed as Coefficient of Performance (COP).

COP = $\dfrac{\text{Chiller Cooling Load (kw)}}{\text{Chiller power consumption , (kW)}}$

Energy Efficiency Ratio (EER) = $\dfrac{\text{Cooling or Heating Capacity (Btu/hr)}}{\text{Electric power (w)}}$

Calculation of Water-Cooled Central Chilled Water System Energy Efficiency

- Water-cooled central chilled water system energy efficiency is defined as the ratio of the instantaneous total power consumption by the chillers, chilled water pumps (such as primary, secondary, tertiary etc.), condenser water pumps and cooling towers to the instantaneous total cooling load produced by the central chilled water system.

$$\text{Cooling load of central chilled water system, RT} = \sum \text{Individual chiller cooling load, RT} \quad (1.20)$$

Water-cooled central chilled water system energy efficiency, kW/RT:

$$\eta_{system} = \frac{\sum \text{Individual Chiller, CHWPP, CHWSP, CDWP \& CT electric power consumption, kW}}{\text{Cooling load of central chilled water system, RT}} \quad (1.21)$$

where

CHWPP: Chilled Water Primary Pump

CHWSP: Chilled Water Secondary Pump

CT: Cooling Tower

CDWP: Condenser Water Pump

Chiller Performance Based on IPLV, NPLV and Singapore Standards

- **Integrated Part Load Value (IPLV)**
- As Chillers do not always operate at design load and operating conditions, IPLV value predicts chiller efficiency at AHRI standard.

$$IPLV = \frac{1}{\frac{0.01}{A} + \frac{0.42}{B} + \frac{0.45}{C} + \frac{0.12}{D}}$$

where

A = kW/RT at 100% load (*ECW* 29.4 °C / *EDB* 35 °C)

B = kW/RT at 75% load (*ECW* 23.9 °C / *EDB* 26.7 °C)

C = kW/RT at 50% load (*ECW* 18.3 °C / *EDB* 18.3 °C)

D = kW/RT at 25% load (*ECW* 18.3 °C / *EDB* 12.8 °C)

ECW = Entering condenser water temperature for the water-cooled chiller

EDB = Entering dry bulb temperature of the ambient air to the condenser coil of air-cooled chiller

Chiller Performance Based on IPLV, NPLV and Singapore Standards

- **Non-Standard Part Load Value (NPLV)**
- NPLV for chiller efficiency is also calculated using the same Equation for IPLV.

Table 1.1 Minimum efficiency of vapour compression chillers based on Singapore Standard SS530: 2014

Equipment type	Size category	Minimum efficiency, COP (W/W)	
		Path A	Path B
Water-cooled, electrically operated, positive displacement (rotary screw and scroll)	≥ 1055 kW and < 2100 kW	5.771 FL	5.633 FL
		6.770 IPLV	8.586 IPLV
Water-cooled, electrically operated, centrifugal	≥ 1055 kW and < 1407 kW	6.286 FL	5.917 FL
		6.770 IPLV	9.027 IPLV

(Source: Reproduced from Singapore Standard SS530: 2014 with permission from SPRING Singapore. Please refer SS530: 2014 for details. Website: www.singaporestandardseshop.sg)

Singapre Standard SS530:2014

Table 1.3 Operating variables generally used to evaluate the performance of chillers

Operating Variables	Values
Chilled water supply temperature	6.7 °C (44 °F)
Condenser water supply temperature	29.4 °C (85 °F)
Chilled water ΔT at maximum load	5.6 °C (10 °F)
Condenser water ΔT at maximum load	5.6 °C (10 °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)

Table 1.4 Breakdown of minimum efficiency of water cooled chilled water system of capacity ≥ 1055 kW and < 1407 kW (≥ 300 RT and < 400 RT)

Description	Singapore Standards	kW/RT
Water cooled centrifugal chiller (≥ 300 RT and < 400 RT)	SS530: 2014	0.559
Chilled water pumps	SS553	0.053
Condenser water pumps	SS553	0.057
Cooling towers	SS530: 2014	0.054
Water-cooled central chilled water system energy efficiency		**0.723**

Green Mark Criteria for Chiller Plant Efficiency

Green Mark Criteria for Chiller Plant Efficiency					
Water-cooled Chilled Water Systems			Air-cooled Chilled Water Systems		
Green Mark Rating	Peak Building Cooling Load (RT)		Green Mark Rating	Peak Building Cooling Load (RT)	
	< 500 RT	≥ 500 RT		< 500 RT	≥ 500 RT
	Efficiency (kW/RT)			Efficiency (kW/RT)	
Certified	0.85	0.75	Certified	1.10	1.0
Gold	0.80	0.70	Gold	1.00	Not Applicable
Gold Plus	0.75	0.68	Gold Plus	0.85	
Platinum	0.70	0.65	Platinum	0.78	

Chiller Replacement Approach

1. **Age of Chiller**

❖ Older chiller typically have lower efficiency and may be near the end of their useful life.

2. **Operating Costs**

❖ If the operating costs are higher due to inefficiency or frequent repairs, it may be more cost effective to replace the chiller.

3. **Energy Savings**

❖ Never models can offer substantial energy savings, which can offset the initial investment over time.

4. **Environmental Regulations**

❖ Stricter environmental regulations may necessitate replacing older chiller that use refrigerants phased out due to the ozone depletion potential (ODP) or global warming potential (GWP).

5. **Capacity**

❖ If cooling demands have increased, a chiller replacement may be needed to meet the new load requirements efficiently

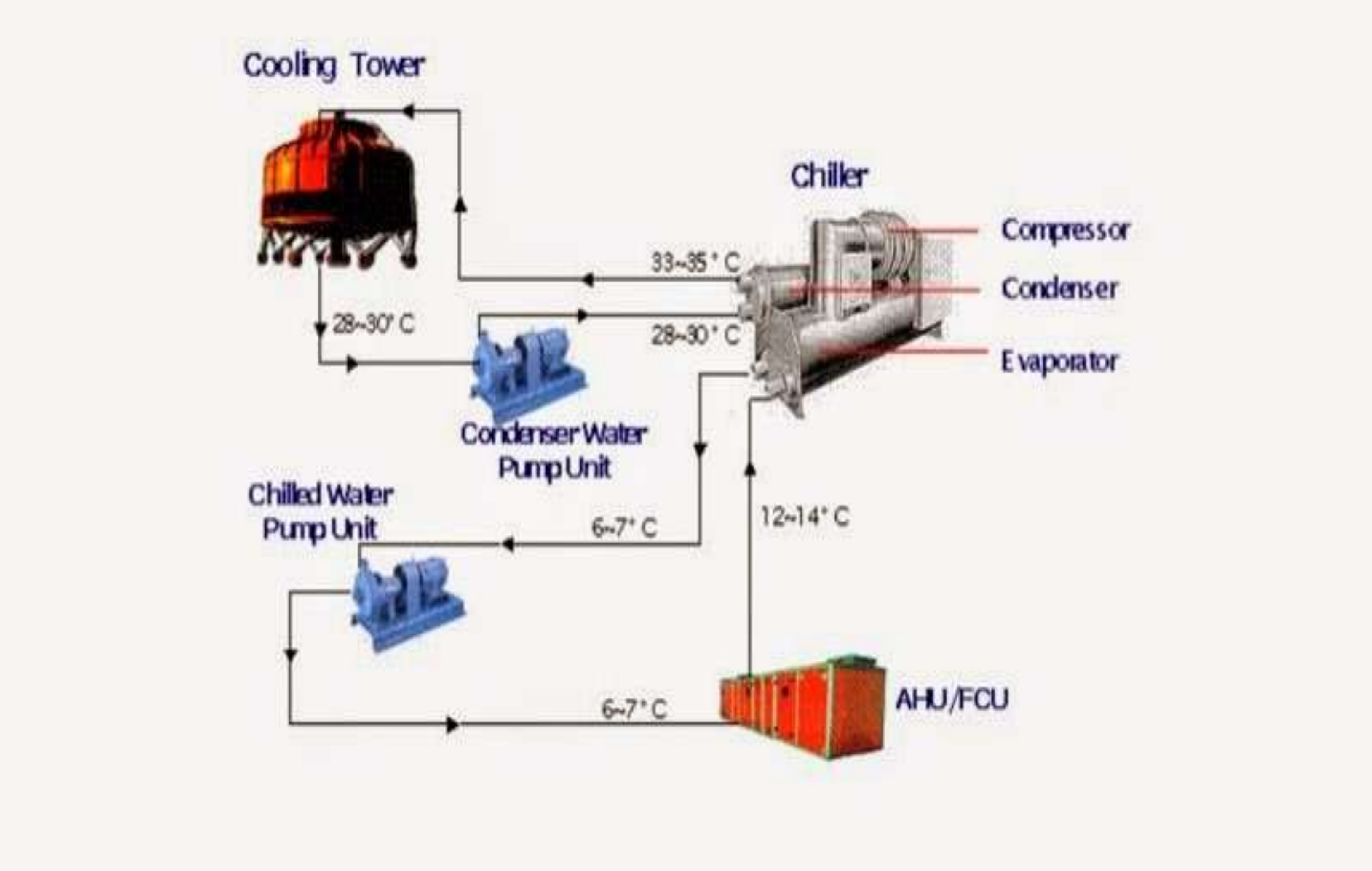
6. **Incentives and Rebates**

❖ In some regions, there may be financial incentives or rebates for upgrading to more energy efficient systems.

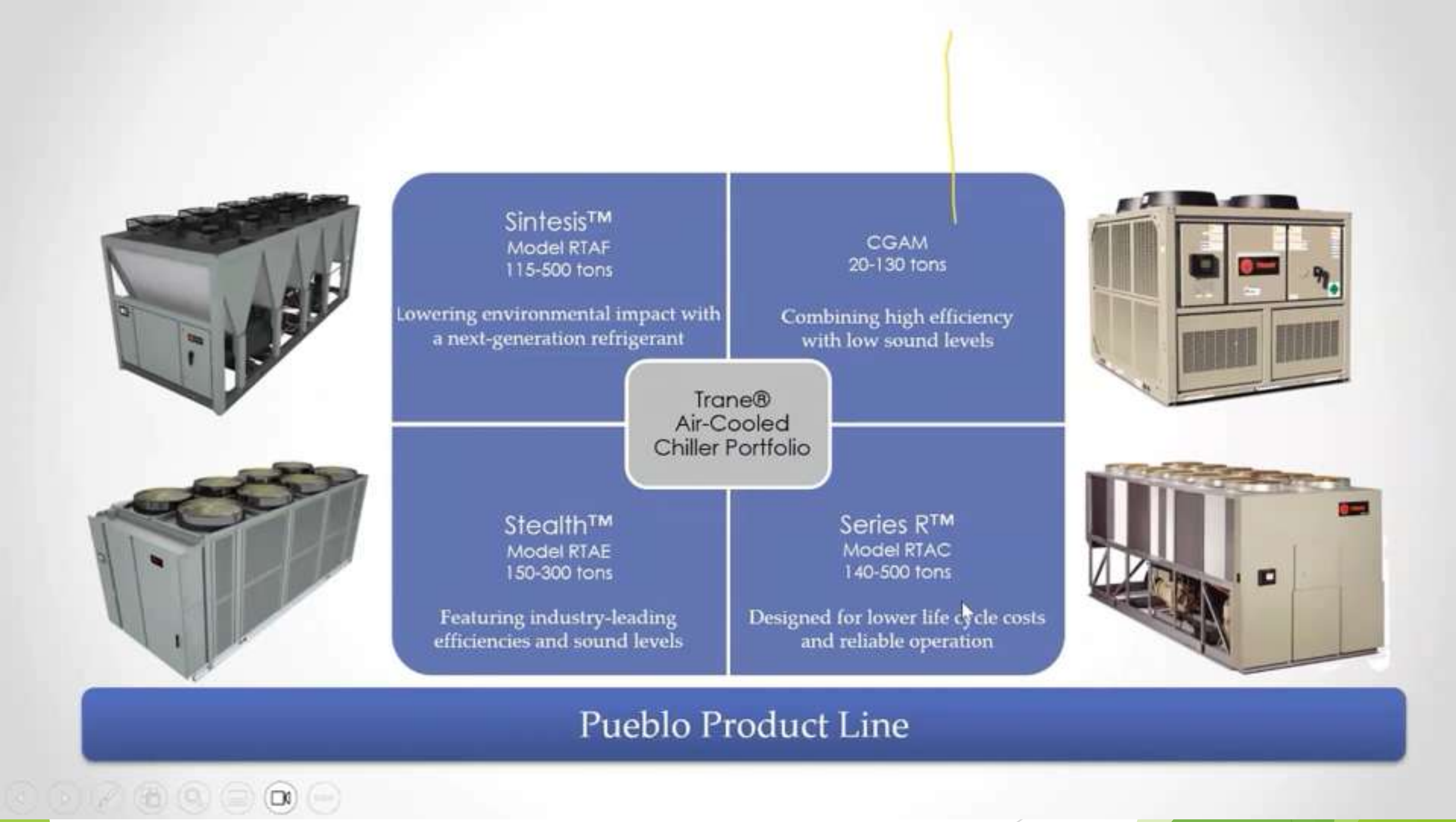
Optimisation of Chilled Water System

- Operating efficiency of chiller depends on :
- 1. Type of Chiller
- 2. Rated efficiency of chiller
- 3. Part-load performance of chiller
- 4. Matching of chiller capacity to the cooling load of the building
- 5. Sub cooling of condenser
- 6. Condition of condenser tube

Air-Cooled to Water-Cooled Chiller



Method of Chilled Water Temperature Reset



Air-Cooled to Water-Cooled Chiller

- Air-Cooled Chiller (ACC) : Condenser coil is cooled by

  Blowing ambient air.

- Water-Cooled Chiller (WCC): Condenser coil is cooled by condenser water which is cooled using the cooling tower.
- The convective heat transfer coefficient for water is higher than air. As a result, the condensing temperature and pressure of the refrigerant in the condenser is lower for WCC, which helps to reduce the compressor lift and the compressor power consumption.
- Typical efficiency of ACC ranges from 1.0 to 1.5 kW/RT and WCC ranges from 0.5 to 0.6 kW/RT.
- First cost of WCC systems is higher than ACC systems as WCC requires plant room, condenser water pumps, cooling towers and condenser water piping systems. Extra initial cost for WCC can be paid back in few years due to higher energy efficiency of WCC.
- ACC can be used small area (Example : Data Centre area, small occupied area).

Example 1.1

Air-conditioning of a building is provided using a 350 RT Air-Cooled Chiller (ACC). The building cooling load from 8am to 10pm and the energy consumption of the ACC are shown in Table 1.5.

Table 1.5 Energy consumption of the existing ACC

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	1.30	325
0900 t0 1000	1	250	1.30	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	1.20	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	1.30	325
1800 to 1900	1	250	1.30	325
1900 to 2000	1	250	1.30	325
2000 to 2100	1	200	1.40	280
2100 to 2200	1	200	1.40	280
			Total	**4809**

Table 1.6 Part load efficiency of the proposed WCC

Load (RT)	Efficiency (kW/RT)
200	0.62
250	0.60
275	0.59
300	0.58
350	0.57

Solution

Using the part load efficiency of the proposed WCC, the estimated energy consumption of the WCC is presented in Table 1.7.

Table 1.7 Estimated energy consumption of the proposed WCC

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	1.30	325	0.60	150
0900 t0 1000	1	250	1.30	325	0.60	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**	**1.20**	420	**0.57**	199.50
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	1.30	325	0.60	150
1800 to 1900	1	250	1.30	325	0.60	150
1900 to 2000	1	250	1.30	325	0.60	150
2000 to 2100	1	200	1.40	280	0.62	124
2100 to 2200	1	200	1.40	280	0.62	124
			Total	**4809**		**2218**

Table 1.8 Calculated electrical energy and water consumption for the condenser water pump and cooling tower

Operating hours	Number of hours	Cooling load, RT	Energy consumption for condenser water pump and cooling tower, kWh	Make-up water consumption for cooling tower, m^3
	A	B	A x B x 0.12 kW/RT	B x 1 x 10^{-2}
0800 to 0900	1	250	30	2.50
0900 t0 1000	1	250	30	2.50
1000 to 1100	1	275	33	2.75
1100 to 1200	1	275	33	2.75
1200 to 1300	1	300	36	3.00
1300 to 1400	1	**350**	**42**	3.50
1400 to 1500	1	300	36	3.00
1500 to 1600	1	300	36	3.00
1600 to 1700	1	300	36	3.00
1700 to 1800	1	250	30	2.50
1800 to 1900	1	250	30	2.50
1900 to 2000	1	250	30	2.50
2000 to 2100	1	200	24	2.00
2100 to 2200	1	200	24	2.00
		Total	**450**	**37.50**

Therefore, extra electrical energy consumption by condenser water pumps and cooling towers = 450 kWh/day

Make-up water consumption of cooling towers = 37.5 m^3/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 pumps and cooling towers, kW/RT

= 350 x (1.2 – 0.57) - 350 x 0.12

= 178.5 kW

To calculate the cost savings, the following utility tariffs can be assumed:

Electricity tariff = $0.20 / kWh

Electricity demand charge = $8 / kW per month

Water usage = $1 / m^3

Net annual cost 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 0.20) – (37.5 x 1)] x 365 + [178.5 x 8 x 12]

= $159,742 per year

Chiller Efficiency & Life Cycle Costing

- Rated efficiency (at 100 % loading) of chillers ranges from 0.5 to 0.65 kw/RT
- Energy cost exceeds the first cost by 10 to 15 times over the operating life.
- High efficiency chillers are expensive but incur low energy cost.
- The additional cost of high efficiency chillers can be paid back in about 3 to 5 years.

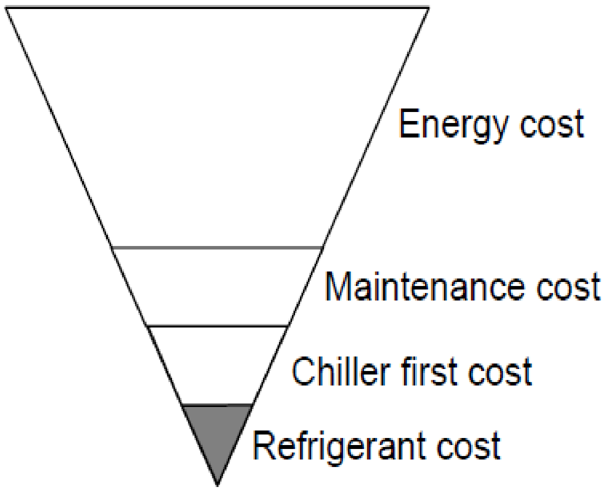


Figure 1.20 Components and relative magnitudes of chiller life cycle costs

Example 1.2

Consider three 600RT capacity chiller options to support the constant process cooling load of 600 RT. The efficiencies and first costs for the three 600 RT chiller options are presented in Table 1.9.

Table 1.9 First costs and rated efficiencies of three 600 RT chiller options

Chiller option	Chiller first cost, $	Chiller efficiency, kW/RT
1	420,000	0.50
2	408,000	0.55
3	390,000	0.65

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

Chiller is to operate 10 hrs/day and 300 days a year

Electricity tariff = $0.20 / kWh

Electricity cost escalation is 2% per year

Solution

For the chiller of efficiency 0.5 kW/RT, the electrical energy cost for year-1

= 10 hours/day x 300 days/year x 600RT x 0.5 kW/RT x $0.20/kWh

= $180,000

As the escalation of electricity tariff is 2% per year, the energy cost for year-2 will be

= $180,000 x (1+0.02) = $183,600

Table 1.10 Life cycle cost for the chiller options

	Option-1, 0.5 kW/RT	Option-2, 0.55 kW/RT	Option-3, 0.65 kW/RT
	$	$	$
Year-0	**420,000**	**408,000**	**390,000**
Year-1	180,000	198,000	234,000
Year-2	183,600	201,960	238,680
Year-3	187,272	205,999	243,454
Year-4	191,017	210,119	248,323
Year-5	194,838	214,322	253,289
Year-6	198,735	218,608	258,355
Year-7	202,709	222,980	263,522
Year-8	206,763	227,440	268,792
Year-9	210,899	231,989	274,168
Year-10	215,117	236,628	279,652
Total	**2,390,950**	**2,576,045**	**2,952,235**

Example 1.3

Consider two 600RT capacity chiller options to support the variable cooling load of a commercial building as shown in Table 1.11. Part load efficiencies for the chiller options are presented in Table 1.12.

Table 1.11 Variation of building cooling load with time

Operating hours	Number of hours	Cooling load, RT
0800 to 0900	1	360
0900 t0 1000	1	450
1000 to 1100	1	480
1100 to 1200	1	540
1200 to 1300	1	600
1300 to 1400	1	600
1400 to 1500	1	540
1500 to 1600	1	480
1600 to 1700	1	420
1700 to 1800	1	360

Table 1.12 Part load efficiency for the chiller options

Chiller load, RT	Loading, %	Chiller-A efficiency, kW/RT	Chiller-B efficiency, kW/RT
600	100	0.50	0.55
540	90	0.52	0.57
480	80	0.55	0.60
420	70	0.59	0.64
360	60	0.60	0.66
300	50	0.67	0.73

Table 1.13 Daily energy consumption for chiller-A of rated efficiency 0.5 kW/RT

Operating hours	Number of hours	Cooling load, RT	Operating chiller capacity, RT	Loading, %	Chiller efficiency, kW/RT	Energy consumption, kWh
	A	B	C	D =100 (B / C)	E	A x B x E
0800 to 0900	1	360	600	60	0.6	216.0
0900 t0 1000	1	450	600	75	0.57	256.5
1000 to 1100	1	480	600	80	0.55	264.0
1100 to 1200	1	540	600	90	0.52	280.8
1200 to 1300	1	600	600	100	0.5	300.0
1300 to 1400	1	600	600	100	0.50	300.0
1400 to 1500	1	540	600	90	0.52	280.8
1500 to 1600	1	480	600	80	0.55	264.0
1600 to 1700	1	420	600	70	0.59	247.8
1700 to 1800	1	360	600	60	0.60	216.0
				Total (kWh/day)		2625.9

Annual energy consumption = 2625 x 250 = 656,475 kwh/year
Annual electricity cost = 656,475 x 0.2 = $ 131,295 / year

Table 1.14 Daily energy consumption for chiller-B of rated efficiency 0.55 kW/RT

Operating hours	Number of hours	Cooling load, RT	Operating chiller capacity, RT	Loading, %	Chiller efficiency, kW/RT	Energy consumption, kWh
	A	B	C	D =100 (B / C)	E	A x B x E
0800 to 0900	1	360	600	60	0.66	237.6
0900 t0 1000	1	450	600	75	0.62	279.0
1000 to 1100	1	480	600	80	0.60	288.0
1100 to 1200	1	540	600	90	0.57	307.8
1200 to 1300	1	600	600	100	0.55	330.0
1300 to 1400	1	600	600	100	0.55	330.0
1400 to 1500	1	540	600	90	0.57	307.8
1500 to 1600	1	480	600	80	0.60	288.0
1600 to 1700	1	420	600	70	0.64	268.8
1700 to 1800	1	360	600	60	0.66	237.6
					Total (kWh/day)	2874.6

Annual energy consumption = 2874 x 250 = 718,650 kwh/year

Annual electricity cost = 718650 x 0.2 = $ 143,730 / year

Table 1.15 Summary of life cycle cost for the two chiller options

	Option-1, 0.5 kW/RT $	Option-2, 0.55 kW/RT $
Year-0	**420,000**	**408,000**
Year-1	131,295	143,730
Year-2	133,921	146,605
Year-3	136,599	149,537
Year-4	139,331	152,527
Year-5	142,118	155,578
Year-6	144,960	158,690
Year-7	147,859	161,863
Year-8	150,817	165,101
Year-9	153,833	168,403
Year-10	156,910	171,771
Total	**1,857,644**	**1,981,803**

Chiller Sizing & Configuration

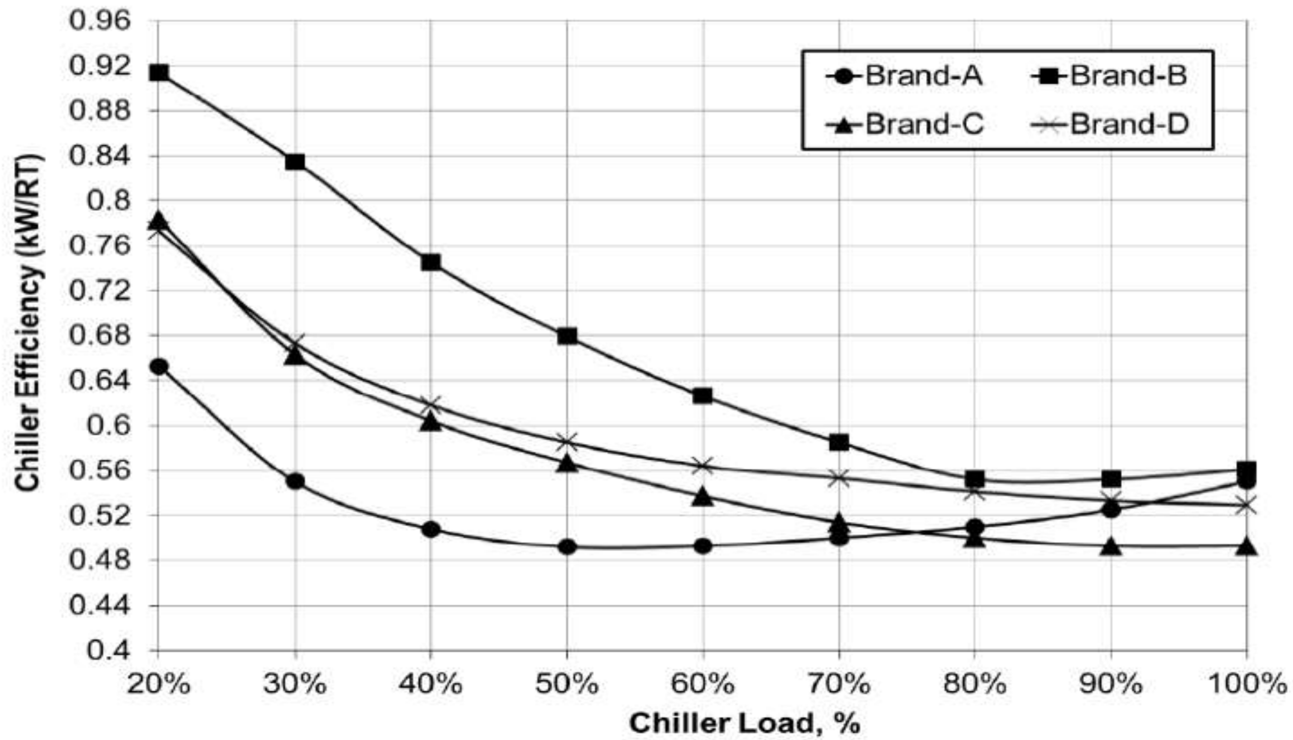


Figure 1.21 Variation of chiller efficiency with loading for chillers of different brands using different types of compressor and refrigerant

Example 1.4

Cooling load profile of a building and the frequencies of cooling load occurrences are shown in Figures-1.22 and 1.23 respectively.

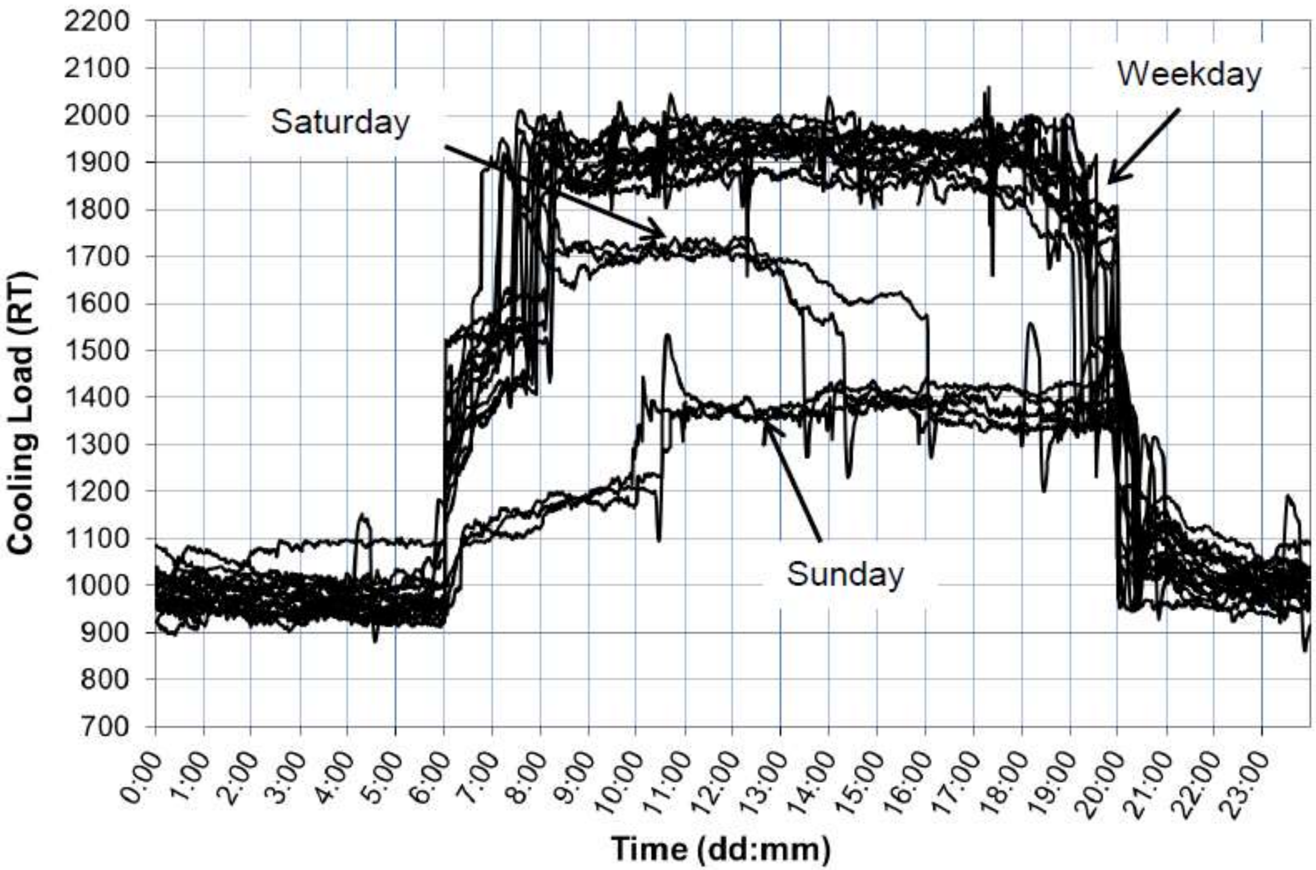


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Figure 1.22 Cooling load profile of a building

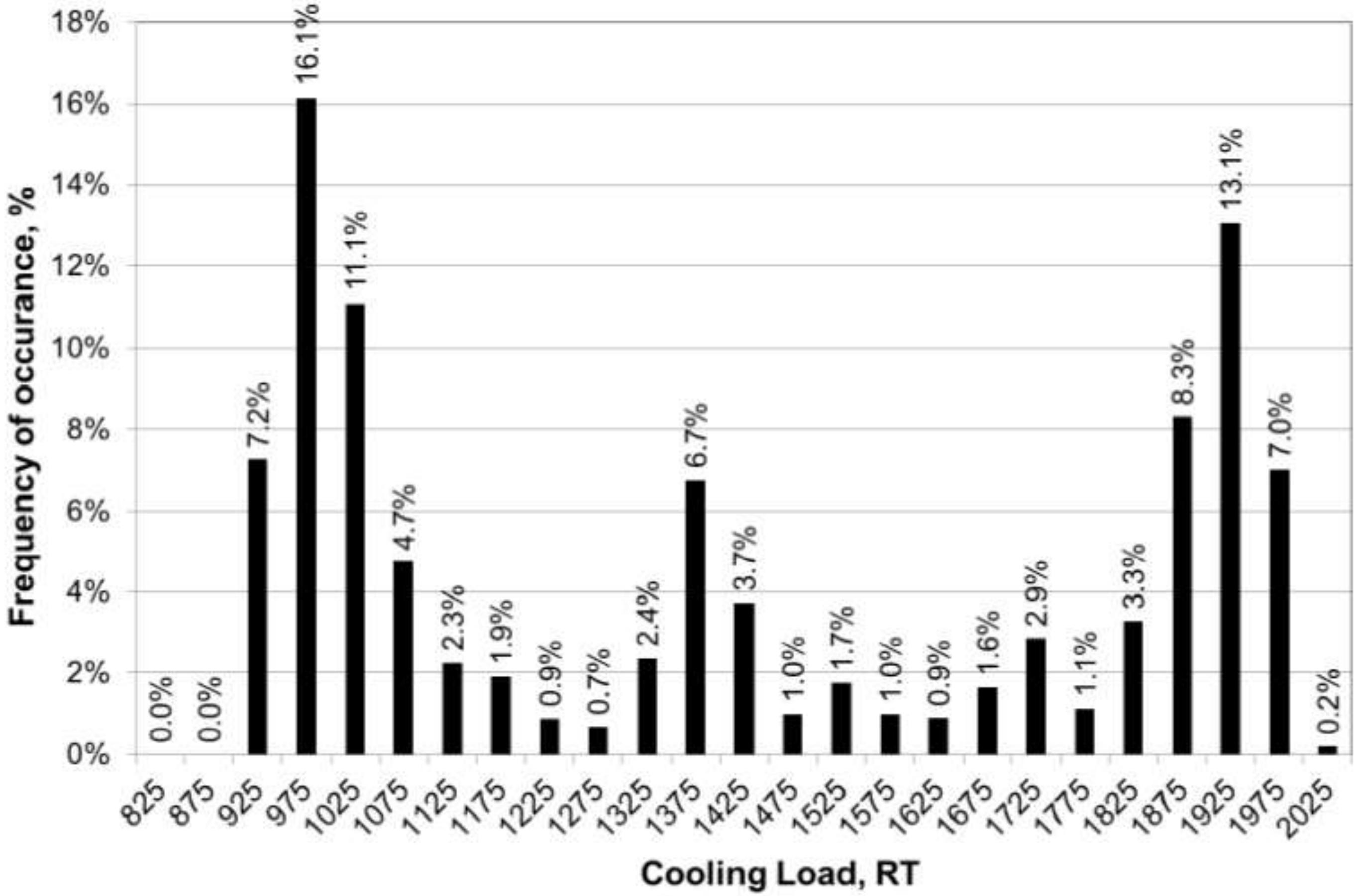


Figure 1.23 Frequencies of cooling load occurrences

Option-1 : 1no of 2050 RT chiller
Option-2 : 2 nos of 1100 RT chillers
Option-3 : 1 no. of 500 RT and 2 nos. of 800 RT Chillers

Table 1.16 Part load efficiencies of chillers

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	0.600	0.586	0.590	0.52
30	0.653	0.639	0.641	0.57
20	0.745	0.755	0.754	0.68

Table 1.17 Daily electrical energy consumption for Option-1 (1 no. of 2050 RT chiller)

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	0.560	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	0.530	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 for option-1 = 18,279 kWh / day

Assuming that the chilled water system is operated for 365 days a year, the annual energy consumption = 18,279 x 365 = 6,671,835 kWh / year

Table 1.18 Daily electrical energy consumption for Option-2 (2 nos. of 1100 RT chillers)

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	0.540	1202.7
1425	0.037	0.89	2x1100	64.8	0.534	680.1
1475	0.010	0.24	2x1100	67.0	0.530	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 for option-2 = 17,888 kWh / day

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

Table 1.19 Daily electrical energy consumption for option-3 (1 no. of 500 RT and 2 nos. of 800 RT chillers)

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	0.530	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	0.530	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**

Average daily energy consumption for option-3 = 18,022 kWh / day

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

Table 1.20 Comparison of energy consumption for three different chiller combinations

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

Peak and Off-Peak Operation

- The off-peak period cooling load is usually quite small in comparison to the peak load.
- Night time (off-peak period) cooling load should be very small in comparison to the day time (peak period) cooling load of an office building.
- In some cases, only the cooling load of data center may need to be supported during the off-peak period.
- However, the cooling load of the office area as well as the data center area need to be supported during the peak period.
- If peak period chillers of higher capacity are operated to support the off-peak period cooling load, the chillers will be running at low part load with poor energy efficiency during the off-peak period.
- Dedicated small “ off-peak chillers” should be installed and operated to maintain good energy efficiency during the off-peak period.

Example 1.5

Peak period (8am to 10pm) cooling load of an office building varies between 1500 to 2000 RT. However, off-peak period (10pm to 8am) cooling load varies between 200 to 250 RT to support the data center area. Presently, a chiller of capacity 600 RT is used to provide cooling during off-peak period and the chiller operating efficiency varies between 1 to 1.2 kW/RT as shown in Table 1.21. Calculate the achievable savings if a new chiller of capacity 300 RT of efficiency 0.56 and 0.58 kW/RT for the loading of 250 and 200 RT respectively is used to provide cooling during the off-peak period.

Table 1.21 Present energy consumption during the off-peak period

Time	Hrs/day	Cooling load (RT)	Present chiller efficiency (kW/RT)	Present chiller consumption (kWh/day)
	A	B	C	A x B X C
2200 to 2300	1	250	1.0	250
2300 to 2400	1	250	1.0	250
0000 to 0100	1	250	1.0	250
0100 to 0200	1	250	1.0	250
0200 to 0300	1	200	1.2	240
0300 to 0400	1	200	1.2	240
0400 to 0500	1	200	1.2	240
0500 to 0600	1	200	1.2	240
0600 to 0700	1	250	1.0	250
0700 to 0800	1	250	1.0	250
Total	10			**2460**

Table 1.22 Achievable energy saving due to the operation of the new 300 RT chiller

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
Annual Savings = 1,156 x 365 days x $ 0.2= $ 84,388

Consolidation of Chilled Water Systems

- Chilled water system's energy consumption can be reduced or the operating performance of the chillers can be improved through the consolidation of the chilled water system.

- Possible opportunities are:
  - Different buildings within one facility (eg. Different blocks of university) having different chilled water systems.
  - Tower block (office area) and podium block (retail area) are served by two separate chilled water systems.
  - Different standalone systems serving specific areas.
  - Larger scale application could be the District Cooling Systems.

Consolidation of Chilled Water Systems

Example 1.6

Cooling loads of Building-A and Building-B are supported by two separate chilled water systems.

1. Chilled water system serving Building-A has 3 x 500 RT chillers and operates from 8am to 9pm. Cooling load varies from 150 to 650 RT as shown in Table 1.23.
2. Chilled water system serving Building-B has 2 x 400 RT chillers and operates from 9am to 9pm. Cooling load varies from 200 to 325 RT as shown in Table 1.24.

Assuming that the energy consumption of the pumps and cooling towers remains the same, estimate the achievable energy savings by consolidating the two chilled water systems.

Table 1.23 Present energy consumption of chilled water system of Building-A

Operating hours	Number of hours	Cooling load, RT	Operating chiller capacity, RT	Loading, %	Chiller efficiency, kW/RT	Energy consumption, kWh
	A	B			C	A x B x C
0800 to 0900	1	500	1 x 500	100.0	0.57	285
0900 t0 1000	1	550	2 x 500	55.0	0.74	407
1000 to 1100	1	600	2 x 500	60.0	0.70	420
1100 to 1200	1	650	2 x 500	65.0	0.72	468
1200 to 1300	1	600	2 x 500	60.0	0.70	420
1300 to 1400	1	600	2 x 500	60.0	0.70	420
1400 to 1500	1	550	2 x 500	55.0	0.74	407
1500 to 1600	1	500	1 x 500	100.0	0.57	285
1600 to 1700	1	500	1 x 500	100.0	0.57	285
1700 to 1800	1	350	1 x 500	70.0	0.68	238
1800 to 1900	1	150	1 x 500	30.0	0.95	143
1900 to 2000	1	150	1 x 500	30.0	0.95	143
2000 to 2100	1	150	1 x 500	30.0	0.95	143
					Total	4,063

Chiller energy consumption serving Building-A = 4,063 kWh/day

Table 1.24 Present energy consumption of chilled water system of Building-B

Operating hours	Number of hours	Cooling load, RT	Operating chiller capacity, RT	Loading, %	Chiller efficiency, kW/RT	Energy consumption, kWh
	A	B			C	A x B x C
0900 t0 1000	1	300	1 x 400	75.0	0.71	213
1000 to 1100	1	325	1 x 400	81.3	0.71	231
1100 to 1200	1	350	1 x 400	87.5	0.68	238
1200 to 1300	1	350	1 x 400	87.5	0.68	238
1300 to 1400	1	325	1 x 400	81.3	0.71	231
1400 to 1500	1	325	1 x 400	81.3	0.71	231
1500 to 1600	1	325	1 x 400	81.3	0.71	231
1600 to 1700	1	300	1 x 400	75.0	0.71	213
1700 to 1800	1	300	1 x 400	75.0	0.71	213
1800 to 1900	1	300	1 x 400	75.0	0.71	213
1900 to 2000	1	200	1 x 400	50.0	0.98	196
2000 to 2100	1	200	1 x 400	50.0	0.98	196
					Total	2,643

Chiller energy consumption serving Library = 2,643 kWh/day

Table 1.25 Energy consumption after chilled water system consolidation

Operating hours	Number of hours	Combined Cooling load, RT	Operating chiller capacity, RT	Loading, %	Chiller efficiency, kW/RT	Energy consumption, kWh
	A	B			C	A x B x C
0800 to 0900	1	500	1 x 500	100.0	0.57	285
0900 t0 1000	1	850	2 x 500	85.0	0.55	468
1000 to 1100	1	925	2 x 500	92.5	0.56	518
1100 to 1200	1	1000	2 x 500	100.0	0.57	570
1200 to 1300	1	950	2 x 500	95.0	0.57	542
1300 to 1400	1	925	2 x 500	92.5	0.56	518
1400 to 1500	1	875	2 x 500	87.5	0.55	481
1500 to 1600	1	825	2 x 500	82.5	0.55	454
1600 to 1700	1	800	2 x 500	80.0	0.57	456
1700 to 1800	1	650	2 x 500	65.0	0.72	468
1800 to 1900	1	450	1 x 500	90.0	0.56	252
1900 to 2000	1	350	1 x 500	70.0	0.68	238
2000 to 2100	1	350	1 x 500	70.0	0.68	238
					Total	5,487

Energy consumption after chilled water system consolidation = 5.487 kwh/day Chiller water system energy savings due to consolidation = (4,063+2,643) -5,487

=1,219 kwh / day x 365

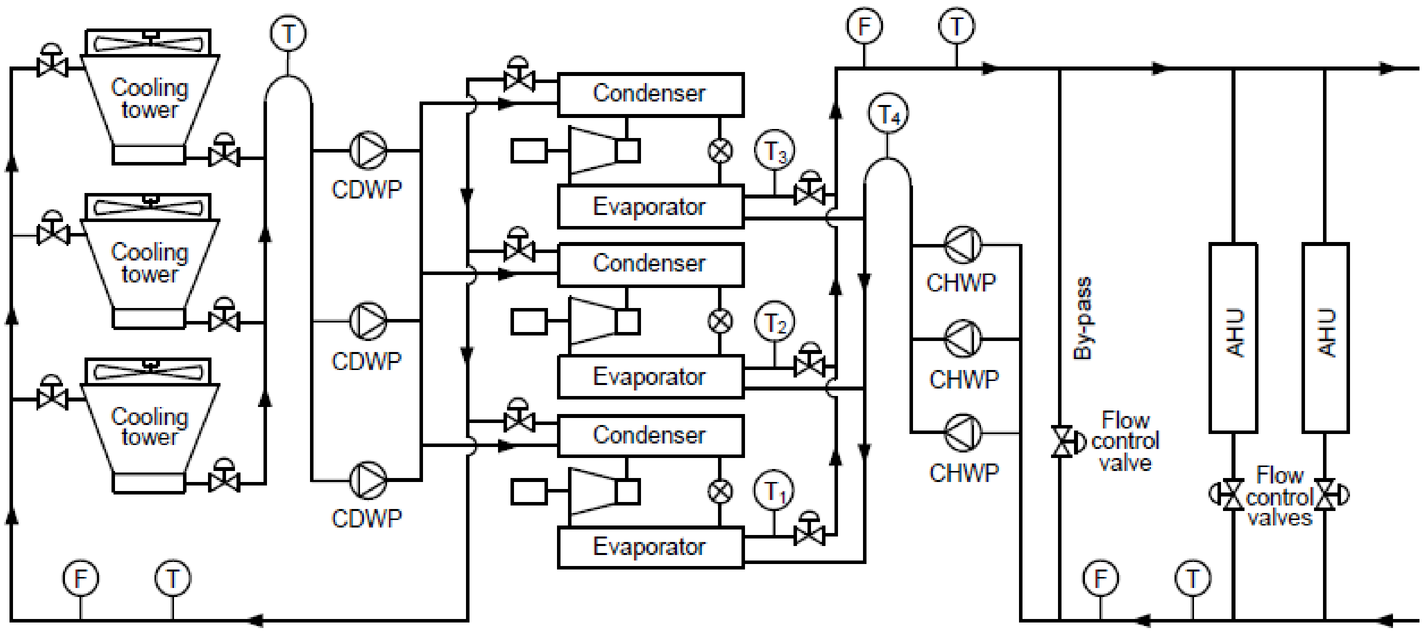
= 444,750 kwh / year

The annual cost saving = 444,750 kwh / year x $ 0.20

=$ 88,950 per year

Chiller Sequencing Strategies

Chiller Sequencing Strategy-1:

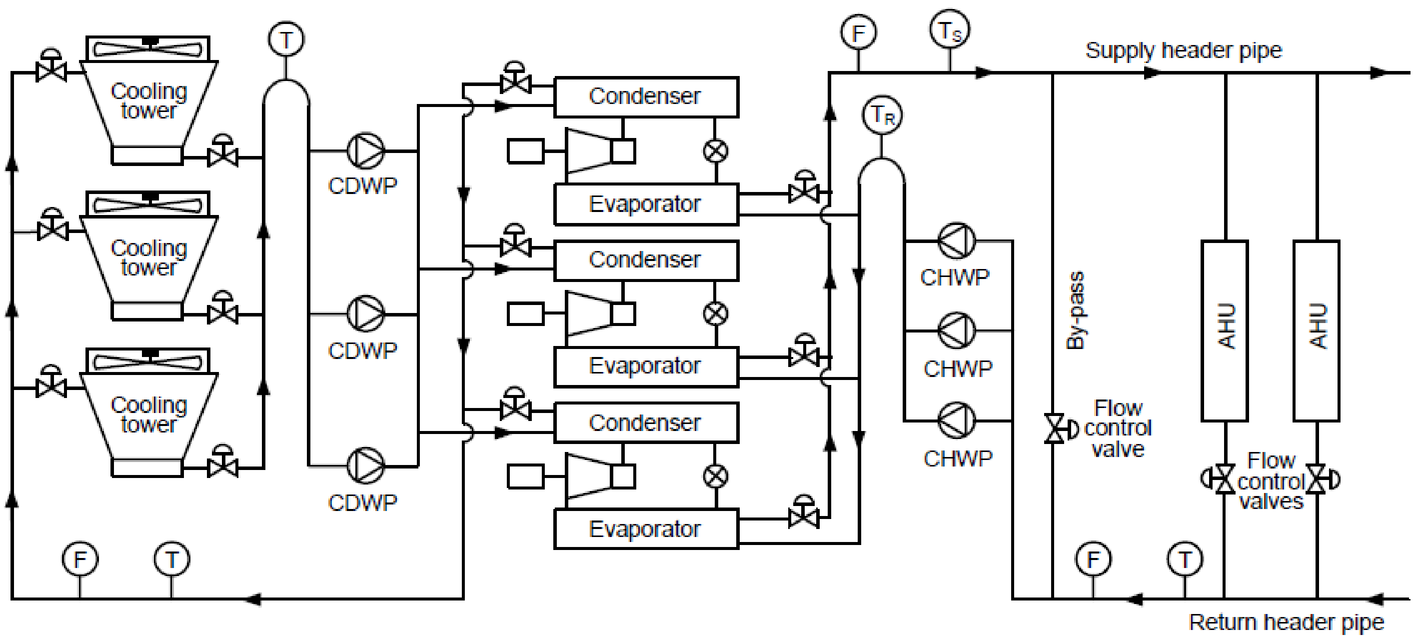


Start another one chiller if:
T_1, T_2 or T_3 is greater than chilled water pre-set supply temperature.

Stop one chiller if:
ΔT (difference between chilled water return T_4 and supply T_1, T_2 or T_3 temperature) is less than a fixed value (0.5 for equal capacity chillers).

Chiller Sequencing Strategies

Chiller Sequencing Strategy-2:



Start another one chiller if:

T_s is greater than chilled water pre-set supply temperature

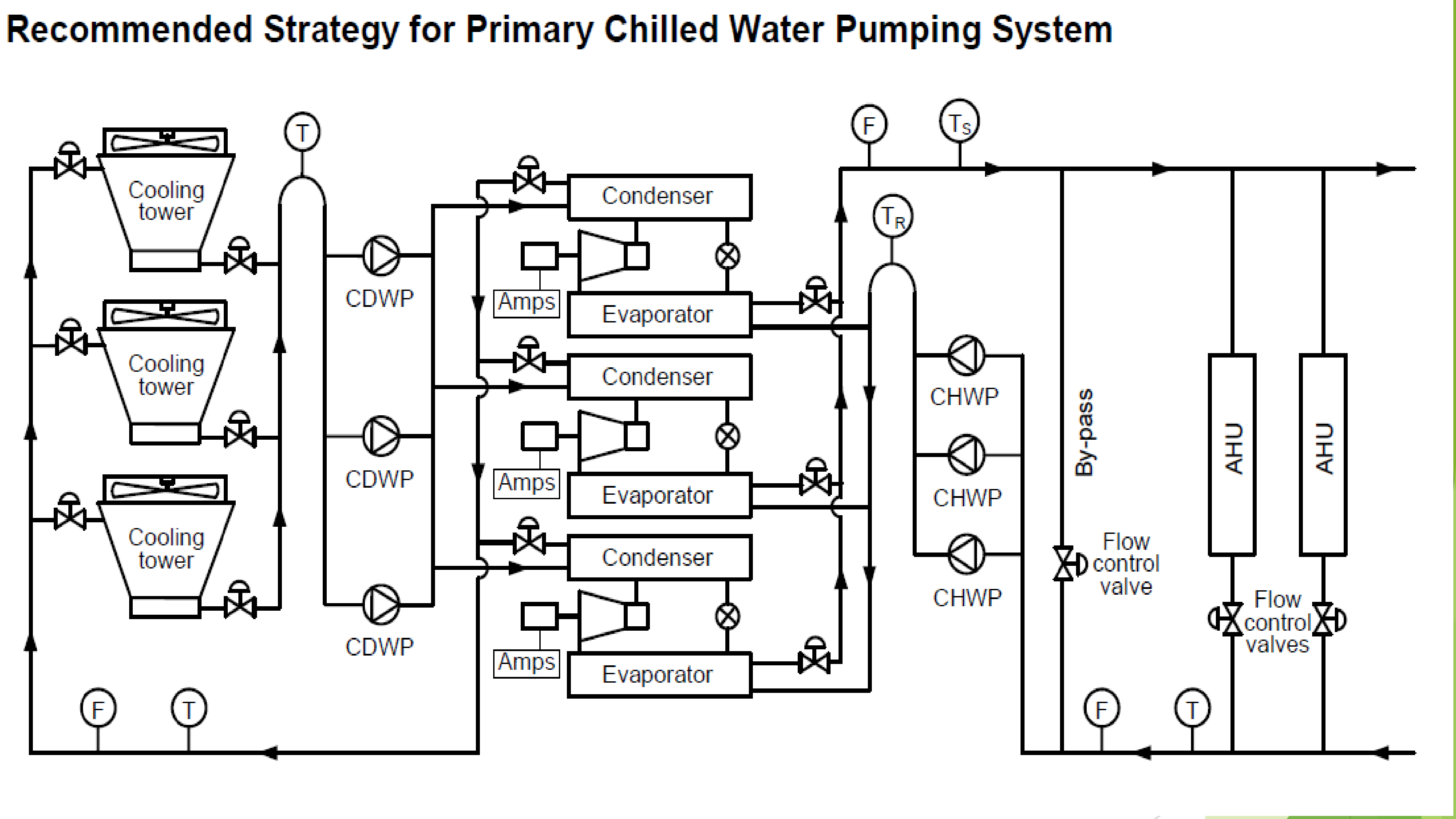
Or

Cooling load = Chiller capacity

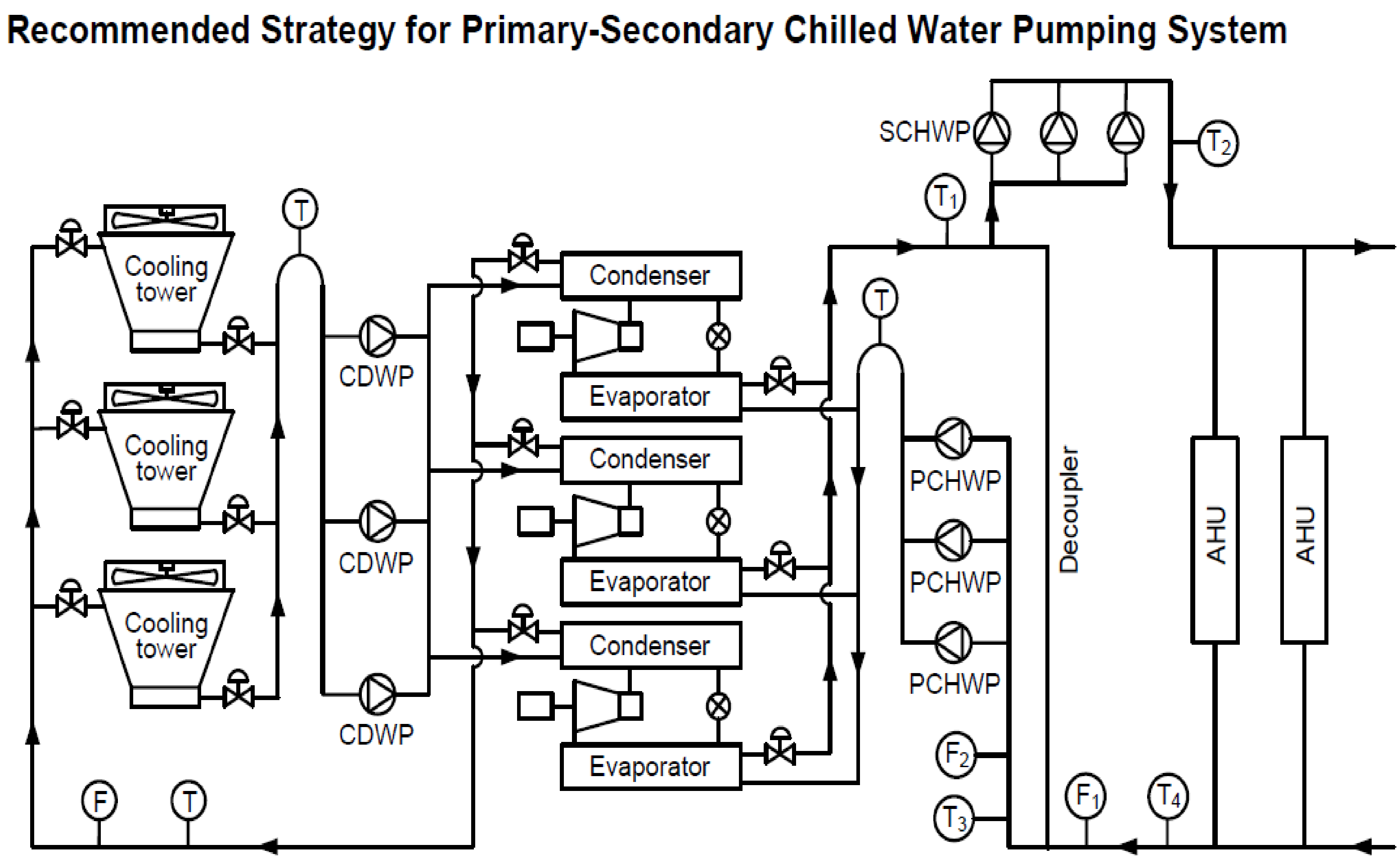
Stop one chiller if:

- Cooling load can be supported by operating 1 no. less chiller
  - Monitor to ensure T_s is not greater than chilled water set point temperature

Chiller Sequencing Strategies



Chiller Sequencing Strategies



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Recommended Chiller Sequencing and Control Strategy.

- Sequencing chillers based on optimum part load efficiency.
- Analysing performance characteristics of chillers under variable chilled and condenser water flow rate and temperature.
- Analysing performance charcteristics of pumps and using appropriate operating and control strategies
- Analysing performance characteristic of cooling towers and fans and using appropriate operating and control strategies
- Analysing performance characteristcs of AHUS, chilled water flow and temperature requirements for AHUs, air conditioning space temperature, relative humidity (RH) and fresh air requirements.

Chiller and Condenser Water Temperature Reset

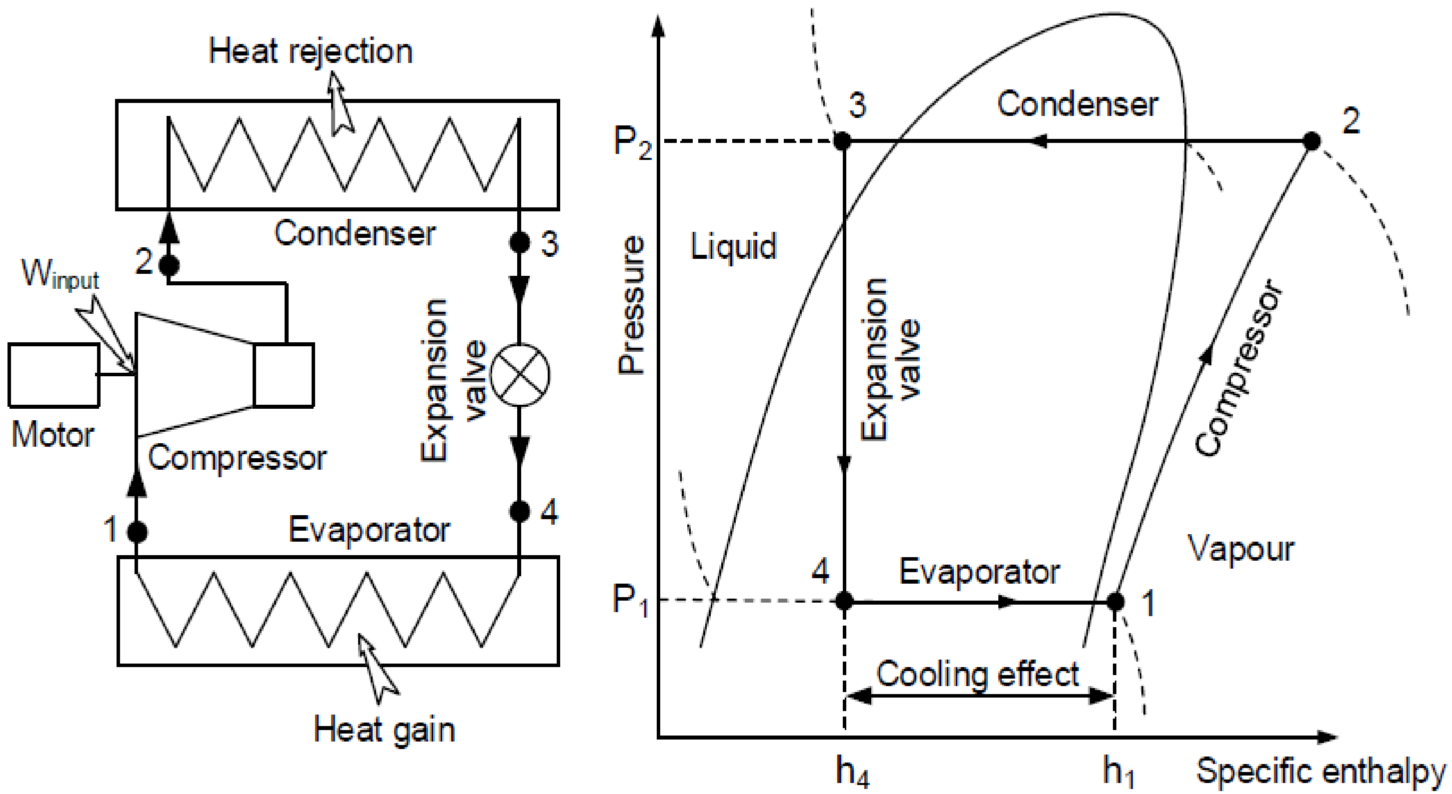

Figure 1.24 Refrigeration cycle of vapour compression air-conditioning systems

Chiller and Condenser Water Temperature Reset

- The power consumption of the compressor depends on the difference of the condenser and evaporator pressure (P2-P1) (also known as compressor lift) and the mass flow rate of refrigerant through the compressor.
- If the difference of enthalpies (h1-h4) is increased, the required mass flow rate of refrigerant through the cycle to get the same cooling effect will be decreased.
- As a result, the power consumption of the compressor to produce the same cooling effect will decrease.
- Chiller efficiency (kW/RT) is defined as the ratio of compressor power consumption to produce unit cooling effect.
- If the power consumption of the compressor is reduced by reducing the value of (P2-P1) or required mass flow rate of the refrigerant is reduced by increasing the cooling effect (h1-h4), the efficiency of the chiller will be increased.

Effect of Chilled Water Temperature Reset

- In general, an improvement in chiller efficiency of about 1 to 2 percent can be achieved by increasing the chilled water supply temperature by 0.6 C due to the reduction of compressor lift and the increase of cooling effect.
- Usually, chilled water systems are designed for chilled water supply temperature of 6.7 C to support the peak cooling load.
- However, peak cooling load generally occurs only for a short period of time.
- Most of the time chillers are operated at part load.
- Under such operating conditions, it is not necessary to supply chilled water at 6.7 C to the cooling coil of AHUs and the chilled water supply temperature can be reset to a higher value.

Chiller and Condenser Water Temperature Reset

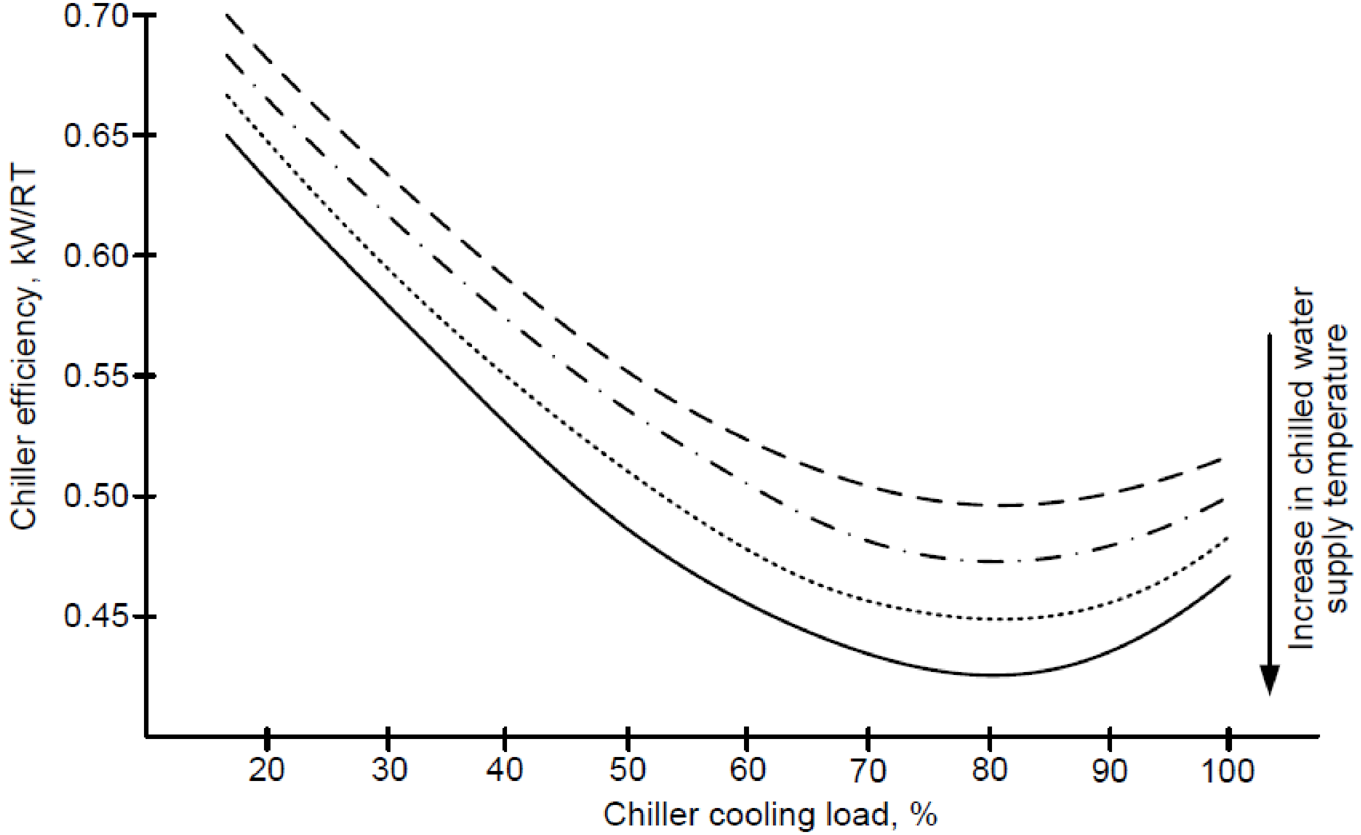

Figure 1.26 Typical variation of chiller efficiency with chilled water supply temperature

Method of Chilled Water Temperature Reset

- For constant air volume (CAV) air handling unit (AHUs), air flow rate across the cooling coils of the AHUs and the space is kept constant irrespective of the cooling load of the spaces.
- The temperature of the supply air is modulated based on the space cooling load.
- If the temperature of the chilled water is increased at low load conditions, volume flow rate of chilled water to the cooling coils of AHUs is required to increase to get the same cooling effect.
- Consequently, power consumption of the variable flow chilled water pumps is increased due to the need for more chilled water flow.
- As expected chiller efficiency improves but chilled water pumping efficiency drops with the increase of chilled water supply temperature.
- The point of minimum overall specific power consumption of the chiller and the chilled water pump represents the optimum chilled water supply temperature.

Method of Chilled Water Temperature Reset

- During the period of low cooling load of the spaces, the chilled water supply temperature can be reset based on:

1. Position of the chilled water flow modulating valve of the cooling coils of AHUs. Chilled water supply temperature can be increased if the modulating valves close more than the pre-set value during the period of low cooling loads of spaces and vice versa.
2. Pre-set value of chilled water return temperature. For constant flow rate of chilled water, during the period of lowing cooling load of the spaces, the chilled water return temperature will be lower than the pre-set value. Under such operating conditions, chilled water supply temperature can be increased.
3. Measured actual cooling load of spaces or outdoor temperature. Heat transfer rate through the building envelope to the air-conditioned spaces decrease with the decreases of outdoor temperature. Chilled water supply temperature can be increased during the period of low outdoor temperature or space cooling load.

Method of Chilled Water Temperature Reset

- Cooling coil of the AHU provides not only sensible cooling but also latent cooling by condensing moisture of the circulating air.
- Moisture removal ability of the AHU depends on the chilled water supply temperature to the cooing coil.
- Due to the increase of chilled water supply temperature, the circulating air flowing across the cooling coil of AHU may not reach to the required dew point temperature.
- Consequently, moisture condensation rate in AHU may drop resulting in higher relative humidity in the air-conditioned spaces.
- On the other hand, for variable air volume (VAV) systems, increases of the chilled water air supply temperature may lead to the increase of the supply air temperature from the AHUs.
- As a result, more air may need to be supplied to the spaces to satisfy the same cooling load.
- This results in higher power consumption of the AHUs.

Method of Chilled Water Temperature Reset

Example 1.7

The average cooling load of a chiller is 1000 RT. Present chilled water supply temperature is 7 ^{0}C and the corresponding chiller efficiency is 0.51 kW/RT. If the chilled water supply temperature is increased to 8.5 ^{0}C, calculate annual energy savings. The chiller is operated 10 hours per day and 350 days of a year. Assume that chiller efficiency is improved by 2% for every 1 ^{o}C increase of chilled water supply temperature.

Solution

Chiller cooling load = 1000 RT

Present chiller efficiency = 0.51 kW/RT

Present chilled water supply temperature = 7 ^{0}C

Proposed chilled water supply temperature = 8.5 ^{0}C

Proposed increment of chilled water supply temperature = 8.5 – 7 = 1.5 ^{o}C

Given that chiller efficiency is improved by 2% for every 1 ^{o}C increase of chilled water supply temperature

Improvement of chiller efficiency due to the increase of chilled water supply temperature by 1.5 ^{o}C = 1.5 x 2 = 3%

Chiller new efficiency = 0.51 kW/RT x (1 – 0.03) = 0.4947 kW/RT

Chiller is operated for 10 hrs/day and 350 days/year

Annual energy savings = (0.51 - 0.4947) x 1000 x 10 x 350 = 53,550 kWh/year

Effect of Condenser Water Temperature Reset

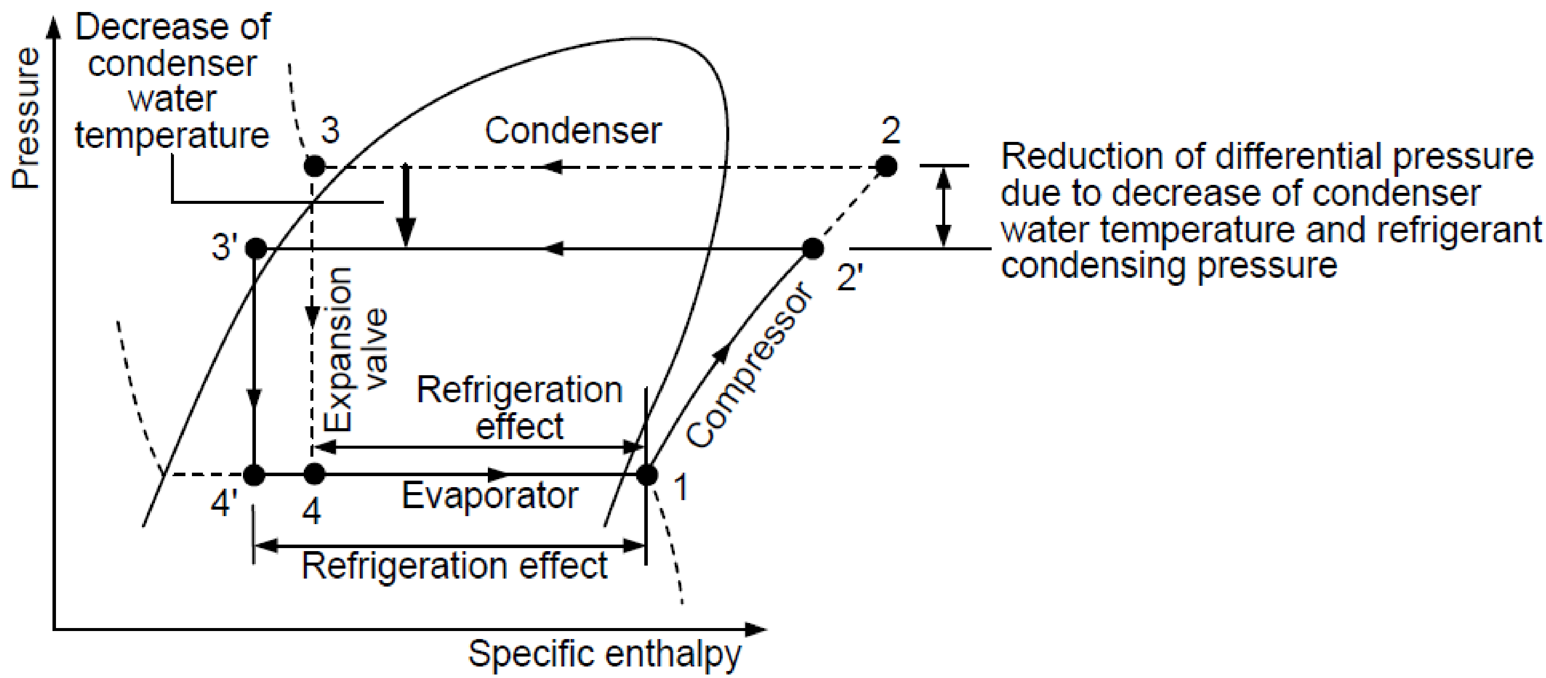

Figure 1.28 Effect of condenser water temperature reset

Effect of Condenser Water Temperature Reset

- Due to the decrease of condenser water supply temperature, the power consumption of the cooling tower will increase.
- The increase of cooling tower power consumption and the reduction of chiller compressor power consumption need to be analysed carefully to determine the net energy saving.
- Same as the chilled water supply temperature, usually an improvement in chiller efficiency of about 1 to 2 percent can be achieved by reducing the condenser water supply temperature by 0.6 C (1 F) due to the compressor lift and an increase of cooling effect.
- To reduce the temperature of condenser water, cooling tower fans are required to operate at higher speed and which results in the increase of the cooling tower fan power consumption.
- As expected, chiller efficiency improves but cooling tower efficiency drops with the decrease of condenser water supply temperature.

Effect of Condenser Water Temperature Reset

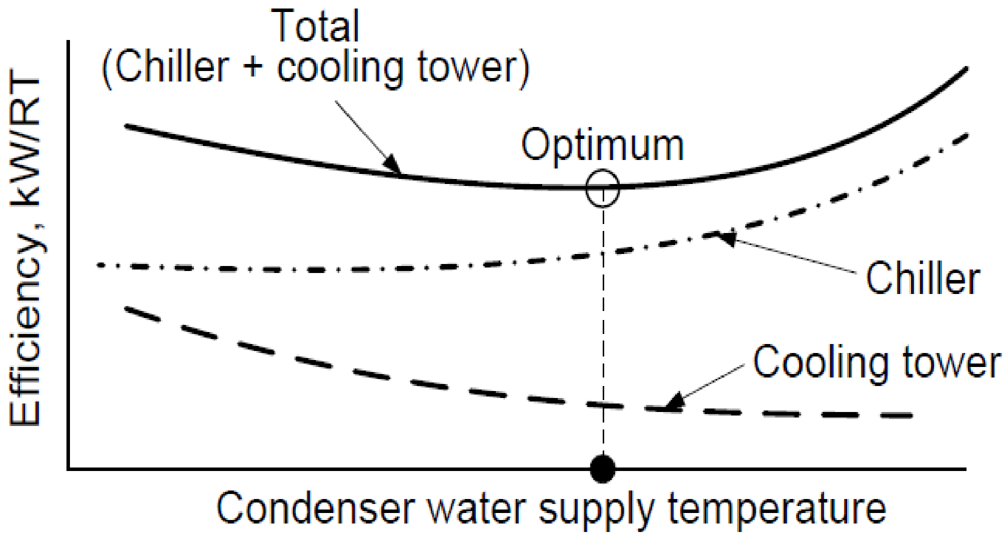

Figure 1.29 Variation of chiller and cooling tower efficiency with condenser water supply temperature

Effect of Condenser Water Temperature Reset

- Wet bulb temperature represents the minimum achievable condenser water temperature.
- If the condenser water is targeted to cool to the wet-bulb temperature, the size of the cooling tower will be extremely large, construction and operating cost will be high.
- As the condenser water temperature reaches closer to the wet bulb temperature, heat transfer rate from the condenser water to the air reduces and hence the power consumption of the cooling tower increases to transfer from the same amount of heat.
- Usually cooling towers are designed to cool the condenser water to about 2 to 3 C higher than the wet bulb temperature.
- If the wet bulb temperature of the ambient air drops, cooling towers can cool the condenser water to a lower temperature which helps to improve the efficiency of the chiller.

Condenser Tube Cleaning and Water Treatment

- Refrigerant rejects heat to the cooling water through the condenser tubes.
- If scale or fouling develops on the tubes surface, the resistance to heat transfer increase.
- As a result, temperature and corresponding pressure of refrigerant in the condenser increases to enhance the driving force of heat transfer, which lowers the efficiency of the chiller.
- Research has shown that the scale of 0.6 mm thickness will increase the chiller compressor power consumption by about 20%.
- It is important to take necessary steps to prevent scaling or fouling and keep the condenser tubes clean,

Condenser Tube Cleaning and Water Treatment

Condenser Tube Cleaning and Water Treatment

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- If scales or fouling develops on the tubes surface, the resistance to heat transfer increases.
- As a result, temperature and corresponding pressure of refrigerant in the condenser increases to enhance the driving force of heat transfer, which lowers the efficiency of the chiller.
- During the heat transfer process in the cooling tower, the condenser water is exposed to the ambient air.
- As a result, dust of ambient air is easily captured by the condenser water.
- Captured dust gradually deposits on the surface of the tubes causing scaling or fouling.
- Research has shown that scale of 0.6 mm thickness will increase the chiller compressor power consumption by about 20 %
- Therefore, it is important to take necessary steps to prevent scaling or fouling and keep the condenser tubes clean.

Condenser Tube Cleaning and Water Treatment

- Water treatment system: The acidity of water is increased using chemical treatment processes to control the alkalinity, which increases the tendency of scaling.
- Water Blow down: Certain percent of condenser water is continuously blown down and clean water is added to maintain the solid content of water below certain level.
- Tube Cleaning: Condenser tubes are cleaned periodically by brushing. The efficiency of chillers returns to the rated value once the tubes are cleaned.

Condenser Tube Cleaning and Water Treatment

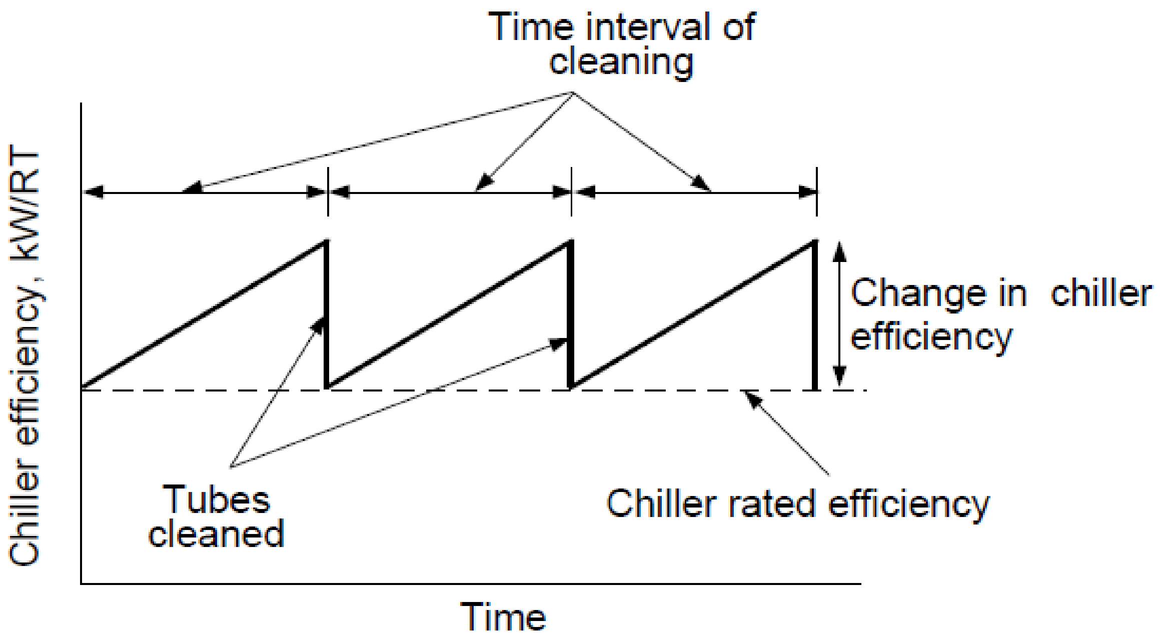

Figure 1.30 Variation of chiller efficiency due to periodic cleaning condenser tubes

Condenser Tube Cleaning and Water Treatment

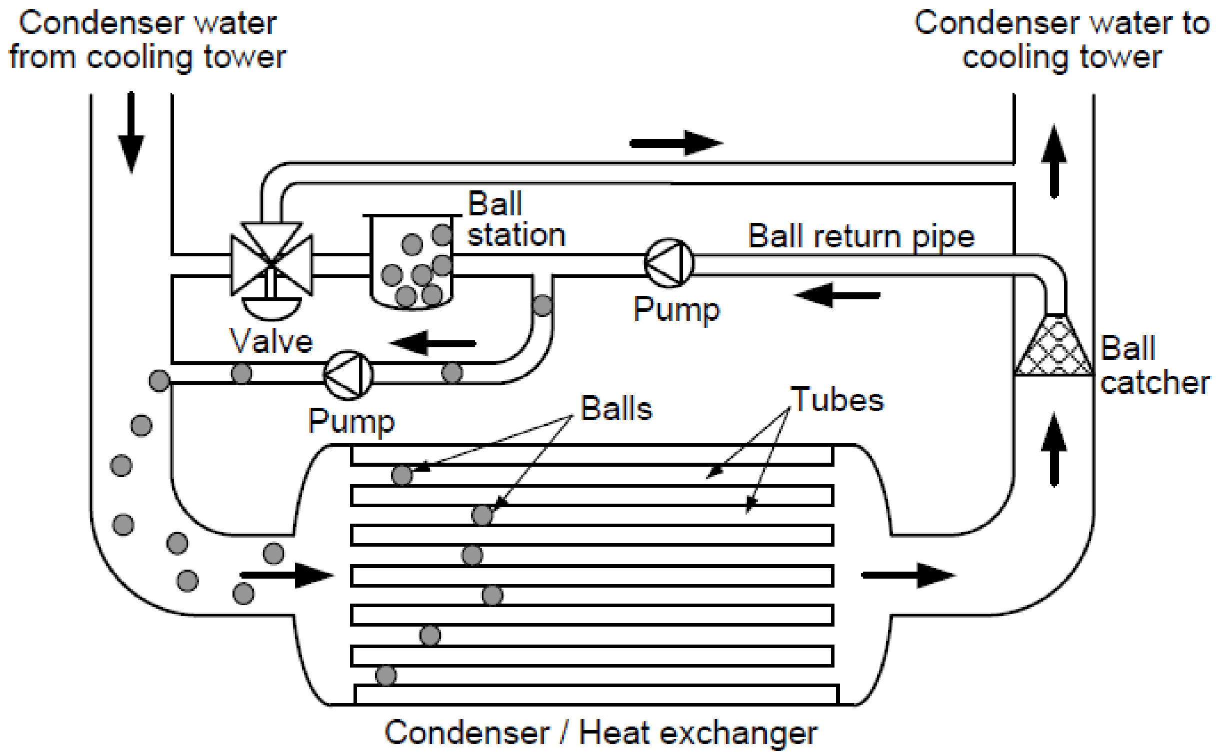

Figure 1.31 Automatic condenser tube cleaning system

Thank You!