Energy Measurement & Audit

Reference Manual

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Preface

“I have been struck again and again by how important measurement is to improving the human condition.” — Bill Gates

Sciences and achievements have a common foundation: Measurement.
What is the right direction, how far do we have to go, how long will we take, how much energy will we require. As engineers, these are questions we constantly ask as we strive to advance our craft. When we ask the right questions, develop new solutions and measure their effectiveness, we will continue to progress.

This manual is intended to broaden your knowledge in the practice and discipline of energy audit and analysis of mechanical systems in commercial and industrial facilities. The manual is divided into eight main chapters:

1. The Need for Energy Measurement and Analysis (EM&A)
2. Introduction to Different Levels of Energy Measurement and Analysis (EM&A)
3. Overview of Measurement Instruments
4. Measurement and Analysis of Chilled water system
5. Measurement and Analysis of AHUs, FCUs and Mechanical Ventilation Systems
6. Lighting Systems
7. Industrial Systems
8. Data Plotting and Analysis Assignments
9. Safety Considerations

I believe they will provide a good foundation for Energy Managers to evaluate energy efficiency of facilities, as well as develop and implement energy efficiency measures and verify their effectiveness.

Some of the material in this manual (listed below) has been obtained with kind permission from Spring Singapore, Building Construction Authority of Singapore and Air Movement and Control Association:

1. SS591-2013: Code of practice for long term measurement of central chilled water system energy efficiency.
2. SS530-2014: Code of practice for energy efficiency standard for building services and equipment

3. SS553-2009: Code of practice for air-conditioning and mechanical ventilation in buildings
4. Green Mark for Non-Residential Buildings (New and Existing)
5. AMCA Publication 203: Field Performance Measurement of Fan Systems

I would like to extend my sincere gratitude to my fellow authors, Ms Teng Seer Ping, Ms May Pwint and Dr Md Raisul Islam, all of whom have contributed tremendously to the development of this manual. Much credit also goes to the editing and proof reading work done by Ms April Khor and the dedicated team from National Environment Agency, The Institution of Engineers, Singapore and Building Construction Authority. Without them, this manual would certainly not have been possible.

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1 The Need for Energy Measurement and Analysis (EM&A)

Introduction

As Singapore is renewable-energy constrained and imports virtually all of our energy, our primary strategy to reduce our carbon footprint and energy cost, and improve our energy resilience is to improve our energy efficiency.

One of the fundamental actions required to improve energy efficiency is to measure and verify how efficiently energy is being used. The data from accurate measurement will provide the knowledge to hone energy efficiency skills and also provide data to develop a reliable financial business case that can motivate management to invest with confidence.

The need for EM&A can be aptly summed up by two frequently used quotes:

“You cannot manage what you do not measure.”

“What gets measured, gets done.”

Learning Outcomes

Participants will be able to:

i. Understand the importance of EM&A
ii. Be aware of standards and legislative requirements for energy measurement and management.

1.1 The Opportunity Cost of Poor EM&A

EM&A can be simply defined as a process to measure and analyse where a facility consumes energy with an intention to identify areas of inefficiencies and propose measures to improve efficiencies.

The cost of EM&A can often be high. Consider for example, the EM&A of a chilled water system shown below.

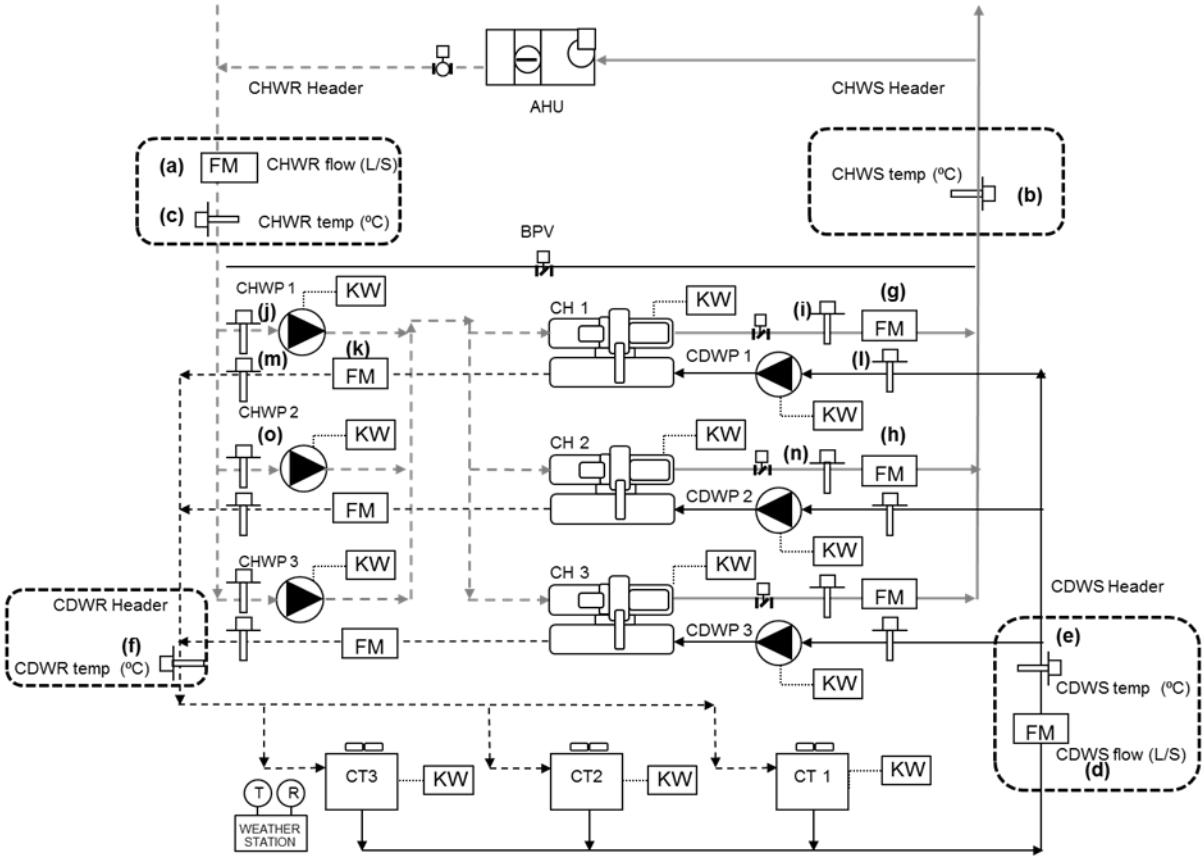


Figure 1.1: *Example of Chilled Water System Configuration*
(Source: SPRING Singapore)

To determine the efficiency of each chiller, pump and cooling tower, an energy manager will need to carry out the following tasks:

a. Hot-tap four outlets per chiller for insertion of temperature sensors. Two for chilled water (CHW) supply and return, and two for condenser water (CDW) supply and return.
b. Hot-tap two outlets per CHW header for insertion of temperature sensors.
c. Hot-tap two outlets per CDW header for insertion of temperature sensors.
d. Hot-tap two outlets per CHW header for connection of differential pressure transmitter.

e. Hot-tap two outlets per CDW header for connection of differential pressure transmitter.
f. Install two flow meters per chiller
g. Install one flow meter at each CHW header and CDW header
h. Install power meters for each chiller, CHW pump, CDW pump and cooling tower.
i. Skilled labour to erect scaffold, carry out hot-tapping, install wiring, remove and put back insulation.
j. Skilled programmer to set up the data logger, temperature sensors, flow meters, power meters, pressure transmitters and to download the data.
k. Licensed Electrical Worker to supervise the installation of power meters in the Motor Control Centre (MCC) panel.
l. Professional to carry out the analysis of the data.

The cost of manpower and instruments for the above mentioned works will typically amount to more than ten thousand dollars.

The high cost has led to many in management to question whether there is a need for such energy audits. However, the cost of electricity to operate the chilled water system is far larger than the cost of investing in EM&A. Take a chilled water system with an average cooling load of 1000RT operating continuously. If the chilled water system efficiency is 1.0 kW/RT and electricity cost $0.20/kWh, the annual energy cost would be equal:
1000RT x 8760 hrs/year x 1.0 kW/RT x $0.20/kWh = $1.75M

Assuming a new chilled water system with new chillers, CHW pumps, CDW pumps, cooling towers and controls will cost approximately $2,000/RT. A 1000RT chilled water system will cost approximately $2 million.

The energy cost to operate an inefficient chilled water system per year can be equivalent to the cost to purchase a new chilled water system each year.

The results from an early batch of National Environment Agency (NEA) funded energy audits in 2005 showed that most water-cooled chilled water systems were operating at an efficiency poorer than 1.20 kW/RT. Most of the facility owners were not even aware that their chilled water systems were operating so poorly and therefore had not taken any actions to make improvements. This is the opportunity cost of poor EM&A.

Figure 1.2 illustrates an example of poor EM&A leading to high energy cost for a chilled water system of a semi-conductor factory. The wrong reading from the CHW return temperature

sensor led to the wrong computation of cooling load, and led to more chillers operating than necessary. This resulted in a waste of 3,504,000 kWh / year or $700,800 per year. (Assuming that energy cost is $0.20/kWh and chilled water system operates 8,760 hours/year)

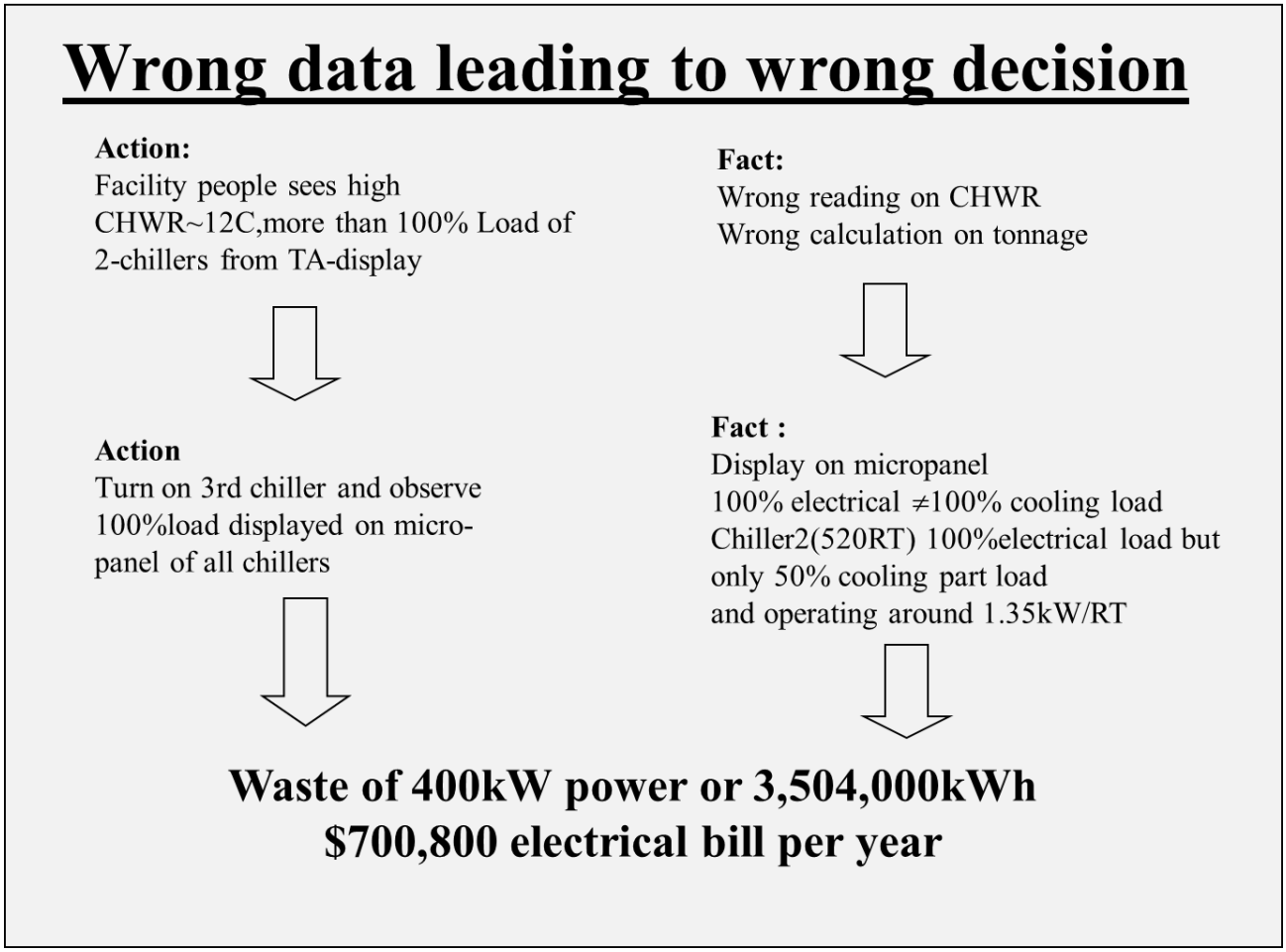


Figure 1.2: *Example of Poor EM&A Leading to High Energy Cost*

1.2 What Is Good EM&A and How It Helps To Improve Energy Efficiency

Some would agree that the foundation of good engineering is the unit of measurement. It quantifies the attributes of the world in a precise and repeatable way that provides the foundation of engineering to progress.

Similarly, the foundation for energy efficiency to progress is also the unit of measure. Without the discipline of continuous and accurate EM&A, it is literally impossible to improve energy efficiency.

A growing body of data shows that better EM&A results in significantly higher levels of energy efficiency, greater persistence of energy efficiency over time and lower variability of energy efficiency. Logically this makes sense, since real time measurement at multiple measurement points provides building managers with a strong diagnostic tool that allows them to better understand, monitor and adjust energy systems to maintain and even increase the energy efficiency of the building over its life cycle.

Good EM&A should encompass the following characteristics:

a. It must account for both energy consumption and energy efficiency. Examples of energy consumption and energy efficiency metrices for common mechanical services in buildings are shown in the figure below:

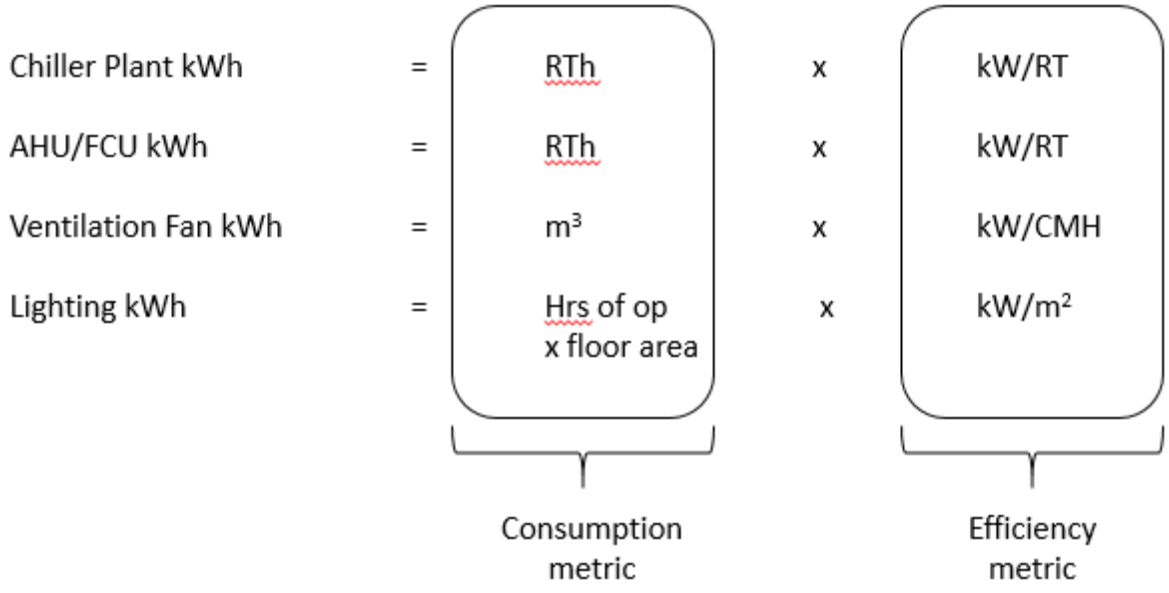


Figure 1.3: *Energy Consumption and Energy Efficiency Matrices*

b. The level of uncertainty of the EM&A must be commensurate with the level of savings expected from EM&A and the energy conservation measures. For example, a project has an expected savings of $100,000 per year and that a basic EM&A approach had an accuracy of no better than ±25% with 90% confidence, or $25,000 per year. To improve the accuracy to within $10,000 it may be seen as reasonable to spend an extra $5,000 per year on EM&A but not $30,000 per year. The quantity of savings at stake therefore places limits on the target expenditure for EM&A.

c. The EM&A system should be continuous for systems with variables that changes significantly with time. For instance, if the EM&A is for a system where the energy use varies both across day and seasons, as with a chilled water system, a continuous EM&A system would be required. However, if the EM&A is for a system that is operated according to a well-defined schedule under a constant load, such as a constant-speed exhaust fan motor, the period required to determine annual savings could be quite short.

d. The EM&A system should meet the minimum standards adopted by the regulators, facility owners and designers.

1.3 Key Standards Regarding EM&A

There are several Singapore Standards that provide energy efficiency and energy measurement related guidelines which an energy manager should be familiar with. The key standards are listed below. This section will highlight the key parts of these standards that concern EM&A and is not intended to provide all or the latest information regarding the standards. For complete and latest information, please refer to the prevailing published standards.

a. SS591-2013: Code of practice for long term measurement of central chilled water system energy efficiency
b. SS530-2014: Code of practice for energy efficiency standard for building services and equipment
c. SS553-2016: Code of practice for air-conditioning and mechanical ventilation in buildings
d. BCA Green Mark for Non-Residential Buildings (New and Existing)

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1.3.1 SS591-2013: Code of practice for long term measurement of central chilled water system energy efficiency

Data Points

The minimum and recommended data points for a central chilled water system to be measured are shown below. The data points need to be monitored at 1 minute interval and trended over the entire life-cycle of the chilled water system.

Minimum Requirements	
Temperature	CHW & CDW header return/supply temperature
Flow	CHW & CDW header flow
Power	Power consumption of group of equipment (chillers, CHW & CDW pumps and cooling towers)
Weather Station	Dry-bulb air temperature and RH Minimally 1 set along the cooling towers

Recommended Requirements	
Temperature	CHW & CDW return/supply temperature at individual chillers CDW supply temperature of each cooling tower cell
Flow	CHW & CDW flow at individual chillers
Power	Power consumption of individual equipment

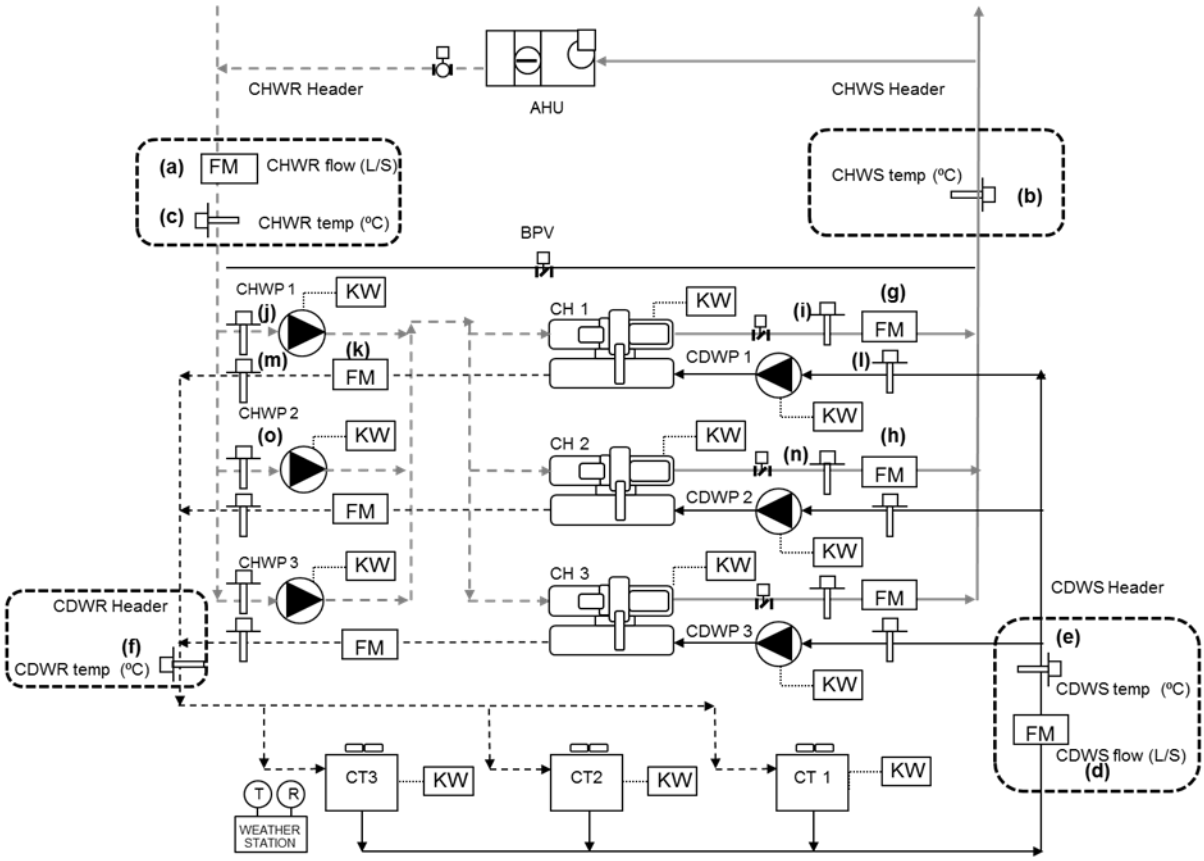


Figure 1.4: *Data Points for chilled water system*

Performance Indicators

The minimum required and recommended performance indicators are shown below.

Minimum Requirements
System cooling load
Supply chilled water temperature
Temperature difference between chilled water supply and return
Total heat rejected
Heat balance substantiating test
Chilled water system energy efficiency (kW/RT)

Equipment energy efficiency (kW/RT) for chillers, chilled water pumps, condenser water pumps and cooling towers

Recommended Requirements
Individual chiller energy efficiency (kW/RT)

Measurement Uncertainty

The maximum allowable uncertainty for each and overall measurement system under laboratory conditions are shown below:

Measurement System (includes sensor and data acquisition system)	**Maximum allowable uncertainty (%) (calibration under laboratory condition)**
Temperature	Each temperature measurement system: **±0.05^{0}C**. Between the supply and return of the chilled or condenser water: $\frac{\sqrt{(0.05^\circ C)^2 + (0.05^\circ C)^2}}{5.5^\circ C} \times 100\% =$ **± 1.3**
Flow	**±1**
Power	**±2**
Overall	Overall maximum allowable uncertainty of the M&V system : $\sqrt{1.3^2 + 1^2 + 2^2} =$ **± 2.6**

The uncertainty of measurement shall include the uncertainty of the entire chain of measurement i.e. sensor, transmitter, wiring, data acquisition system, etc.

Calibration Standards and Uncertainty

The calibration standards and uncertainty of each type of measurement are shown below:

Measurement System	Important clauses
Temperature	Each temperature sensor shall be individually calibrated against a measurement standard with a maximum uncertainty rating of $\pm 0.01^0$C.
Flow	All tests conducted to measure the uncertainty of the flow measurement system shall be in accordance with ISO 4185:1980/Cor 1:1993, ISO 8316:1987 or equivalent test standards. **Type-test reports can be accepted** as long as they demonstrate that the requirements mentioned above have been met.
Power	All tests conducted to measure the uncertainty of power meters and their associated current and voltage transformers used in the power measurement system shall be in accordance with applicable test standards, i.e. IEC 62053-22:2003 for digital power meters, IEC 61869-2:2012 for current transformers and IEC 61869-3:2011/IEC 61869-5:2011 for voltage transformers. Equivalent test standards can also be adopted. **Type-test reports can be accepted** as long as they demonstrate that the requirements mentioned above have been met.

For temperature sensor calibration**,** fixed points calibration method is one of the recommended options to be used in the calibration of the temperature sensors. It is recommended that the following references be used during the calibration:

a. Water triple point at 0.01^0C;
b. Standard platinum resistance thermometers (SPRT) with temperature controlled bath at 15.00^0C; and
c. Gallium fixed point cell at 29.765^0C.

Data Acquisition

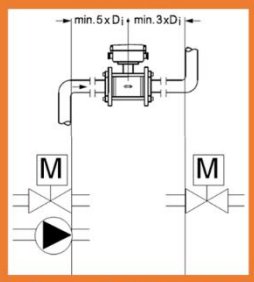
The requirements for data acquisition system are shown below:

Measurement System	Important clauses
Data acquisition system	The data acquisition system shall be able to record and store values up to at least **3 decimal places**. The memory space of the data acquisition system shall be sized for at least **36 months** of storage capacity.

Installation and setup

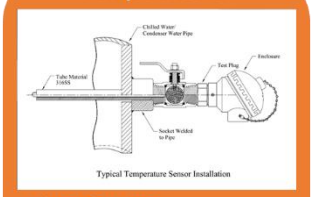
The requirements for installation of instruments are shown below:

Flow meter



For magnetic flow meters

Temp sensors



Typical Temperature Sensor Installation

- Insertion types
- Installed in thermowells
- Sensor in direct contact with water
- Test plugs before and after each temp sensor

Power meters



- Installed at the incoming side of the VSD

Wiring

- All measuring and control cables to have common screen
- Screens of control cables shall be connected to earthing points and from there, to the indoor earthing rings

Testing and Commissioning

The requirements for testing and commissioning are shown below:

Heat Balance substantiating test

- The heat balance shall be within ±5% for 80% of the sampled points measured for a min of 1 week

Multipoint verification checks (header/risers vs chillers)

- **For CHWRT and CDWST**
  - Maximum allowable uncertainty between two temp sensors:

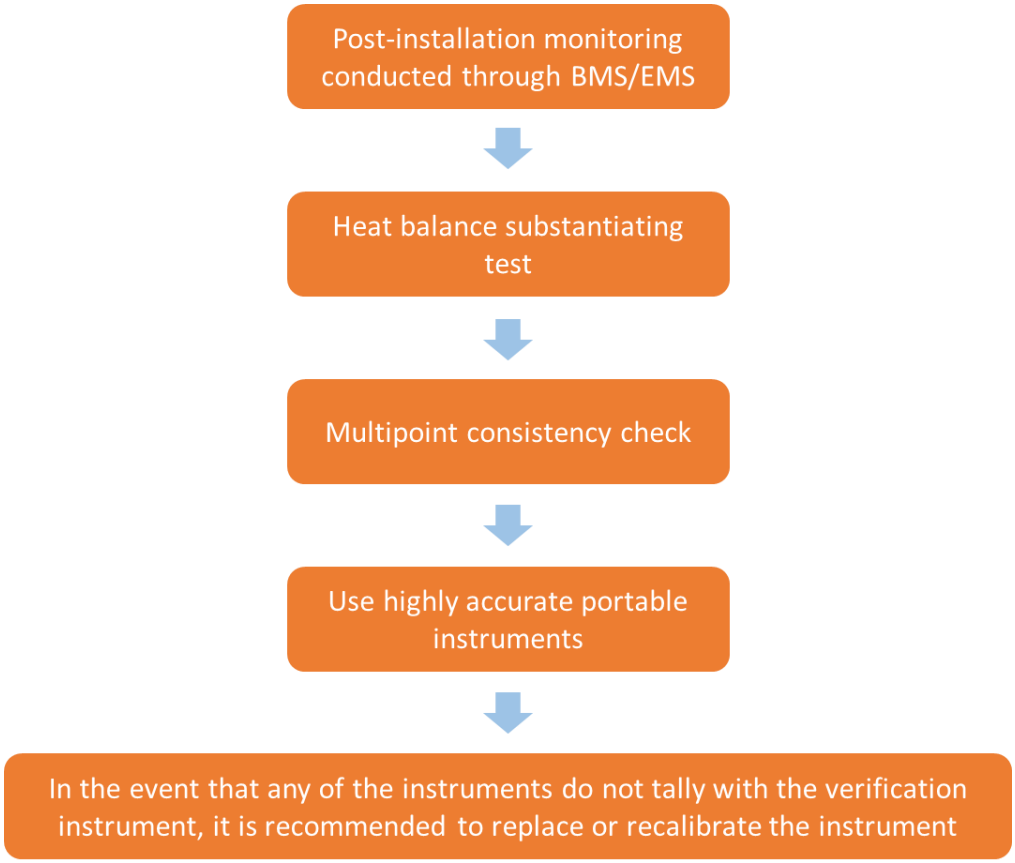
$$\sqrt{0.05°C^2 + 0.05°C^2} = 0.07°C$$

- **For flow**
  - Maximum allowable uncertainty between two flow meters:

$$\sqrt{1\%^2 + 1\%^2} = 1.4\%$$

Long term monitoring

The requirements for long term monitoring are shown below:



1.3.2 SS530-2014 Code of practice for energy efficiency standard for building services and equipment

Minimum Efficiency For Chillers

The minimum efficiencies for chillers are shown below:

Air-Cooled Chiller Minimum Efficiency (kW/RT)

Equipment type	Size category	Path A	Path B
Air-cooled, with condenser, electrically operated	<150 RT	1.178 FL	1.227 FL
	≥150 RT	Refer to SS530 for full table	

Water Cooled Chiller Minimum Efficiency (kW/RT)

Equipment type	Size category	Path A	Path B
Water-cooled, electrically operated, positive displacement (rotary screw and scroll)	<75 RT	0.749 FL	0.779 FL
		0.599 IPLV	0.500 IPLV
	≥75 and <150RT	Refer to SS530 for full table	
	≥150 and <300RT		
	≥300 and <600RT		
	≥600	0.559 FL	0.584 FL
		0.500 IPLV	0.380 IPLV
Water-cooled, electrically operated, centrifugal	<150RT	0.609 FL	0.694 FL
		0.549 IPLV	0.440 IPLV
	≥150 and <300RT	Refer to SS530 for full table	
	≥300 and <400RT		
	≥400 and <600RT		
	>=600RT	0.559 FL	0.584 FL
		0.500 IPLV	0.380 IPLV

FL: Full Load

IPLV: Integrated Part Load Value

One can elect to comply with either Path A or Path B but both FL and IPLV of the selected path must be complied with.

Minimum Efficiency For Cooling Towers

The minimum efficiencies for cooling towers are shown below:

Equipment type	Total system heat rejection capacity at rated conditions	Subcategory or rating condition	Performance required[a]	Test procedure
Propeller or axial fan cooling towers	All	Refer to SS530 for full table		
Centrifugal fan cooling towers	All	35.0 °C entering water 29.4 °C leaving water 23.4 °C wet outdoor air	≥ 1.7 L/s.kW	CTI ATC-105

[a] For the purpose of this table,

- cooling tower performance is defined as the maximum flow rating of the tower divided by the nameplate rated motor power
- air-cooled condenser performance is defined as the heat rejected from the refrigerant divided by the nameplate rated motor power

3.23 L/s.kW is equivalent to (3gpm/RT) / (3.23L/S / kW) x (0.063L/s/gpm) = 0.059KW/RT

Where 3gpm/RT is the standard rated condenser water flow rate in AHRI 550/590.

Minimum Efficiency For Motors

The minimum efficiencies for motors of three different capacities are shown below. Please refer to SS530:2014 for the motors of other capacities.

Power (kW)	**Minimum nominal full-load efficiency (%)**			
	Continuous use[a]		Occasional use[b]	
	2-pole	4-pole	2-pole	4-pole
	IE3 [c]		IE2 [c]	
0.75	80.7	82.5	77.4	79.6
15	91.9	92.1	90.3	90.6
90	95.0	95.2	94.1	94.2

a: 'Continuous use' motors are defined as motors that are used for at least 2900 hours per year

b: 'Occasional use' motors are defined as motors that are used for less than 2900 hours per year.

c: 'IE2' and 'IE3' are efficiency classes of single-speed, induction motors according to IEC 60034-30-1.

Lighting Power Density (LPD)

The lighting power densities for few types of spaces are shown below. Please refer to SS530:2014 for the lighting power densities of other types of spaces.

Interior spaces - Type of usage	**LPD (W/m^2)**
Space-by-space method	
Office work and study	
Offices, meeting rooms, copy/print rooms, class rooms, lecture theatres, computer rooms, reading areas	12
Rest, clean, exercise, play areas	
Hotel guest rooms (including accent, decorative lighting, and spaces within the guest room such as toilets)	12
Toilets, changing rooms, laundries, washing areas	10
Gymnasiums and physical exercise areas	11
Manufacturing and maintenance	
Mechanical and electrical rooms	10.0

1.3.3 SS553-2016 Code of practice for air-conditioning and mechanical ventilation in buildings

Chilled Water and Condenser Water Pump Power Limitation

The chilled water and condenser water pump power limitation shall be as follows:

Reference to AHRI-550/590	
Chilled Water Pump	**Condenser Water Pump**
349 kW/m^3/s or 0.053 kW/RT	301 kW/m^3/s or 0.057 kW/RT
349 kW/m^3/s is equivalent to (349kW//m^3/s) x (2.4 gpm/RT) x (0.0000631 cms/gpm) = 0.053 kW/RT Where 2.4gpm/RT is the standard rated chilled water flow rate in accordance to AHRI-550/590.	301 kW/m^3/s is equivalent to (301kW//m^3/s) x (3.0 gpm/RT) x (0.0000631 cms/gpm) = 0.057 kW/RT Where 3.0gpm/RT is the standard rated condenser water flow rate in accordance to AHRI-550/590.

Reference to AHRI-551/591	
Chilled Water Pump	**Condenser Water Pump**
349 kW/m^3/s or 0.0587 kW/RT	301 kW/m^3/s or 0.0632 kW/RT
Q = mCdt Performance baseline for CHWP is [1000kg/m^3 x 4.192J/(gK) x 5 K] / [349k(J/s)/(m^3/s)] = 60.06 Hence, 3.517kW/RT/ 60.6 = 0.0586kW/RT Where the standard rated chilled water delta T in accordance to AHRI-551/591 is 7°C to 12°C and specific heat capacity of water at 10°C is 4.192kJ/kgK	Q = mCdt Performance baseline for CWP is [1000kg/m^3 x 4.178J/(gK) x 5 K] * (2.4/3) / [301k(J/s)/(m^3/s)] = 55.52 Hence, 3.517kW/RT/ 55.52 = 0.0633kW/RT Where the standard rated condenser delta T in accordance to AHRI-551/591 is 30°C to 35°C and specific heat capacity of water from 30°C to 35°C is 4.178kJ/kgK

Motors exceeding 3.7 kW shall have controls and/or devices (such as variable speed control) that will result in pump motor demand of no more than 30% of design wattage at 50% of design water flow.

Fan Power Limitation For AHUs / FCUs

The fan power limitation for AHUs / FCUS shall be as follows:

Constant volume	**Variable volume**
Allowable nameplate motor power per unit volume flow rate of air	
0.47 W/CMH or 1.7 kW/m^3/s	0.67 W/CMH or 2.4 kW/m^3/s
0.47 W/CMH is equivalent to (0.47 W/ m^3/h) x 3600 (m^3/h / m^3/s) x 1/1000 (kW/W) = 1.7 kW/m^3/s	0.67 W/CMH is equivalent to (0.67 W/ m^3/h) x 3600 (m^3/h / m^3/s) x 1/1000 (kW/W) = 2.4 kW/m^3/s

Note: Power Input method with adjustment factor A can be used instead of Nameplate method. Refer to table 2a and 2b of SS553-2016 for Adjustment Factor A.

Individual VAV fans with motors 7.4 kW and larger shall meet one of the following requirements:

a. Be driven by an electrical variable speed drive;

b. Have other controls and devices for the fan that will result in fan motor demand of less than 30% of design wattage at 50% of design air volume when static pressure setpoint equals one-third of the total design static pressure based on manufacturer's certified fan data.

Fan Power Limitation for Mechanical Ventilation System

The fan power limitation for mechanical ventilation system shall be as follows:

Constant volume and variable volume
Allowable nameplate motor power per unit volume flow rate of air
0.35 W/CMH or 1.26 kW/m^3/s
0.35 W/CMH is equivalent to (0.35 W/ m^3/h) x 3600 (m^3/h / m^3/s) x 1/1000 (kW/W) = 1.26 kW/m^3/s

Note: Power Input method with adjustment factor A can be used instead of Nameplate method. Refer to table 2a and 2b of SS553-2016 for Adjustment Factor A.

Individual VAV fans with motors 7.4 kW and larger shall meet one of the following requirements:

a. Be driven by a mechanical or electrical variable speed drive or the fan shall be a vane-axial fan with variable pitch blades;

b. Have other controls and devices for the fan that will result in fan motor demand of less than 30% of design wattage at 50% of design air volume when static pressure setpoint equals one-third of the total design static pressure based on manufacturer’s certified fan data.

Energy Metering and Instrumentation

Sub-system measurement devices with remote capability (including current sensors or flow meters) shall be provided and shall measure energy consumption data of each sub-system in accordance with table below. Sub-systems that are 10% below the thresholds are exempted.

Use (total of all loads)	Sub-systems thresholds
ACMV systems	Connected electrical loads > 100 kVA
ACMV systems	Connected gas or district services loads > 150 kW
People moving	Sum of all feeders > 50 kVA
Lighting	Connected load > 50 kVA
Process and plug loads	Connected loads > 50 kVA
Process loads	Connected gas or district services load > 75 kW

All building meters and measurement instruments shall be able to communicate energy consumption and metered data to a meter data management system. Meters shall provide a minimum of daily data and shall record a minimum of hourly consumption of energy and measured data.

Outdoor Supply Air Requirement For Comfort Air Conditioning

The minimum outdoor supply air requirements for comfort air-conditioning are as follows:

Type of building/ Occupancy	**Minimum outdoor air supply**
	l/s per m^2 floor area
Restaurants	3.4
Dance halls	Refer to SS553 for full table
Offices	
Shops, supermarkets and department stores	
Theatres and cinemas seating area	
Lobbies and corridors	
Concourses	
Hotel guest rooms	
Classrooms	
Primary school children and above	
Childcare centres	2.8

Outdoor Air Supply for Mechanical Ventilation In Non Air-conditioned buildings

The minimum outdoor air supplies for mechanical ventilation in non-air-conditioned buildings are as follows:

Type of building/ Occupancy	**Minimum outdoor air supply air-change/h**
Offices	6
Restaurants, canteens	Refer to SS553 for full table
Shops	
Workshops, factories	
Classrooms	
Car parks	
Toilets, bathrooms	
Lobbies , concourse, corridors, staircases and exits	
Kitchens (commercial, institutional and industrial)	20

1.3.4 BCA Green Mark for New Non-Residential Building GM NRB:2015

Air-Conditioning Minimum Total System and Component Efficiency

a) Air cooled chilled-water system / Unitary air-conditioning system

Relevant equipment: Air-cooled chillers, chilled-water pumps, variable refrigerant flow systems, single-split units, multi-split units, air distribution system (e.g. AHUs, FCUs, PAHUs).

BCA Green Mark Rating	Peak Building Cooling Load (RT)		Remarks
	< 500 RT	≥ 500 RT	(η_c, η_a) shall meet their respective thresholds. η_c: System kW/ton excluding the air distribution equipment η_a: Air distribution equipment kW/ton $\eta_t = \eta_c + \eta_a$ DSE: Design Total System Efficiency
	Minimum DSE (kW/RT): η_t (η_c, η_a)		
Gold	NA (0.9, NA)	NA (to be assessed on case by case basis)	
Gold^{PLUS}	1.10 (0.85, 0.25)		
Platinum	1.03 (0.78, 0.25)		

b) Water cooled chilled-water system

Relevant equipment: Water-cooled chillers, chilled-water pumps, condenser water pumps, cooling towers, air distribution system.

BCA Green Mark Rating	Peak Building Cooling Load (RT)		Remarks
	< 500 RT	≥ 500 RT	(η_c, η_a) shall meet their respective thresholds. η_c: System kW/ton excluding the air distribution equipment η_a: Air distribution equipment kW/ton $\eta_t = \eta_c + \eta_a$
	Minimum DSE (kW/RT): η_t (η_c, η_a)		
Gold	NA (0.75, NA)	NA (0.68, NA)	
Gold^{PLUS}	0.95 (0.7, 0.25)	0.9 (0.65, 0.25)	
Platinum	0.93 (0.68, 0.25)		

c) District cooling system (DCS)

Relevant equipment: DCS plant (e.g. chillers, chilled-water, condenser water pumps, cooling towers, network pumps, thermal storage, heat exchangers, renewable energy or energy recovery systems within the plant vicinity), building air distribution system.

BCA Green Mark Rating	Minimum DSE (kW/RT): η_t (η_c, η_a)	Remarks
Gold	0.9 (0.65, NA)	(η_c, η_a) shall meet their respective thresholds. η_c: System kW/ton excluding the air distribution equipment η_a: Air distribution equipment kW/ton $\eta_t = \eta_c + \eta_a$
Gold^{PLUS}	0.9 (0.65, 0.25)	
Platinum		

Permanent Instrumentation for the M&V of Chilled Water Air-Conditioning Systems

Permanent M&V instrumentation requirements are as follows:

a. Location and installation of the measuring devices to meet manufacturer's recommendations.
b. All data logging with capability to trend at 1 minute sampling time interval, and recorded to the 3rd decimal digit.
c. Computation and display of air-side efficiency, water-side efficiency and total system efficiency.
d. Full-bore magnetic in-line flow meters, with 1% uncertainty and capable of electronic in-situ verification to within ±2% of its original factory calibration, shall be provided for chilled-water and condenser water loop. Where circumstances do not allow the installation of magnetic in-line flow meters, ultrasonic flow meters may be used.
e. Temperature sensors shall be provided for chilled water and condenser water loop with end-to-end measurement uncertainty within ±0.05 ^{o}C over the entire measurement / calibration range. Thermo-wells shall be installed in a manner that enables the sensors to be in direct contact with fluid flow. Each temperature measurement location shall have 2 spare thermo-wells located at both sides of the sensor for verification of measurement accuracy.
f. Dedicated power meters (of IEC Class 1 or equivalent) and associated current transformers (Class 0.5 or equivalent) shall be provided for monitoring of the power consumption of each of the following groups of equipment where applicable: chillers, chilled water pumps, condenser water pumps, cooling towers, air distribution sub-system (i.e. AHUs, PAHUs, FCUs).

Chilled water system Heat Balance Substantiating Test

The requirement for heat balance substantiating test is as follows:

More than 80% of the computed heat balance over the entire normal operating hours as defined below shall be within 5% over a one week period.

Normal operating hours:

Type of building	**Normal operating hours**
Office building	Monday to Friday: 9am to 6pm
Retail malls	Monday to Sunday: 10am to 9pm
Hotel building	Monday to Sunday: 24 hours
Other building types	To be determined based on operating hours

1.3.5 BCA Green Mark for Existing Non-Residential Building v 3.0

1.3.5.1 Minimum Air-conditioning Plant Operating System Efficiency

The minimum chilled water system operating system efficiencies (kW/RT) are as follows:

Type of system	Water cooled		Air cooled or Unitary	
Cooling Load	< 500RT	≥ 500RT	< 500RT	≥ 500RT
Certified	0.85	0.75	1.10	1.00
Gold	0.80	0.70	1.00	NA
Gold ^{plus}	0.75	0.68	0.85	NA
Platinum	0.70	0.65	0.78	NA

For operating hours of:

Office: Mon to Fri, 9am to 6pm

Retail malls: Mon to Sun, 10am to 9pm

Hotels: Mon to Sun, 24 hours

Other building types: To be determined based on operating hours

Fan Power Limitation for Air-conditioning System

The fan power limitation for AHUs and FCUs (W/CMH) are as follows

Constant volume system	0.47
Variable volume system	0.74

Water-Cooled and Air-Cooled Chilled-Water Plants Permanent M&V Instrumentation Requirements

Permanent M&V instrumentation requirements are as follows:

a. Location and installation of the measuring devices to meet the manufacturer's recommendation.
b. Data acquisition system to have a minimum resolution of 16 bit.
c. All data logging with capability to trend at 1 minute sampling time interval.
d. Dedicated digital power meters shall be provided for the following groups of equipment: chiller(s), chilled water pump(s), condenser water pump(s) and cooling tower(s).
e. Flow meters to be provided for chilled-water and condenser water loop and shall be of ultrasonic / full bore magnetic type or equivalent.
f. Temperature sensors are to be provided for chilled water and condenser water loop and shall have an end-to-end measurement uncertainty not exceeding ± 0.05 °C over

entire measurement or calibration range. All thermos-wells shall be installed in a manner that ensures that the sensors can be in direct contact with fluid flow. Provisions shall be made for each temperature measurement location to have two spare thermo-wells located at both side of the temperature sensor for verification of measurement accuracy.

Chilled water system Heat Balance Substantiating Test

The requirements are the same as BCA Green Mark for New Non-Residential Buildings.

2 Introduction to Different Levels of Energy Measurement and Analysis (EM&A)

Introduction

An energy audit can be simply defined as a process to evaluate where a facility uses energy, and to identify opportunities to reduce its consumption. It is an investigation involving a detailed analysis of energy flows into and out of various systems. The aim is to understand where a facility uses energy, quantify how energy efficient its processes are and to identify and quantify those areas where improvements can be made and estimate the amount of savings achievable. These may include improvements to facility design, operation and management.

Energy audits are commonly performed by Energy Services Companies (ESCOs) to improve the energy efficiency of a facility. Energy auditing plays a vital role in the success of any energy efficiency improvement project and/or energy performance contract (EPC).

There are several types and levels of energy audits performed by ESCOs. Broadly, the different types of audits can be grouped into 3 levels. The general scope of work expected from ESCOs in performing the 3 levels of energy audits is described in this chapter.

Increasingly, facility owners are installing permanent and continuous EM&A systems for major energy consuming systems such as the chilled water system and air handling units. In Singapore, any new building larger than 2000m^2 or any existing building larger than 15,000m^2 undergoing a chiller replacement, is required by the Building Control Act to install a permanent Energy Management System (EMS) for the chilled water system.

Leaning Outcomes

The participants will be able to:

i. Appreciate the different levels of M&A
ii. Appreciate the depth and skills required for each level
iii. Discern which types of M&A to do internally and which to outsource

2.1 Level I Audit

A level I audit, sometimes referred to as a walk through audit, allows the overall energy consumption of the facility to be evaluated. It is expected to give an overview of energy consumption and efficiency, identify low cost Energy Conservation Measures (ECMs), and provide a rough estimate of savings and costs.

The scope of work for level I audit is as follows:

a. Walk through the facility to visually inspect each energy consuming system to identify areas of wastages and inefficiencies
b. Gather operating data from utility bills, existing meters and BMS
c. Analyse energy consumption data, compare to original design and industry benchmarks
d. Identify low cost Energy Conservation Measures (ECMs) that can be implemented readily
e. List down possible capital intensive improvement projects that merit further consideration

<u>Examples of energy wastages</u>

Over cooling

- Excessive hours of operation of air conditioners
- Space temperature too cold
- Infiltration of warm and/or humid air into air-conditioned spaces

Over ventilating

- Excessive hours of operation of AHUs/ FCUs
- Excessive air change
- Excessive outside air ventilation

Over lighting

- Excessive hours of operation of lamps
- Over lit spaces
- Lights left on where it is not required e.g. store room, stair wells, etc.

Examples of energy inefficiencies

Chilled water systems

- Inefficient specifications of chillers, CHW pumps, CDW pumps, cooling towers
- Chillers operating at low load
- High evaporator and condenser approach temperatures implying poor heat exchange
- Set-points not optimised, e.g. CHW supply temperature, header pressure, Variable Speed Drive (VSD) speed, CDW supply temperatures
- No VSDs
- Throttling of pumps
- Cooling towers dirty
- Hot air recirculation for cooling towers implying that heat rejection by cooling towers is inefficient.
- Poor piping implying high pressure losses (e.g. excessive length, right angle bends, small pipe diameters.)

Airside

- Inefficient specification of AHUs, FCUs, fans
- Dirty filters
- Dirty coil
- Set-points not optimised e.g. Supply air temperature, duct static pressure, room temperature
- Control valve faulty
- Temperature sensor at the wrong location or faulty
- No VSDs
- Excessive throttling of airflow
- Poor duct discharge implying high pressure losses

Lighting

- Inefficient lamps (e.g. incandescent, halogen, T12)
- Magnetic ballast
- High light loss fittings implying too much light is trapped within the light fittings

2.2 Level II Audit

A level II audit, sometimes referred to as standard audit, involves short term metering and logging to confirm findings in level I audit, quantify the source of energy to a facility, the amount supplied, what the energy is used for and its efficiency levels. It also identifies areas where savings may be achieved, recommends measures to be taken, and provides a statement of costs and potential savings.

The scope of work for level II energy audits is as follows:

a. Validate and quantify findings in level-1 audit with spot measurements using standard grade handheld instruments
b. Breakdown the building energy use into major sub-systems and quantify the consumption and efficiency for each sub-system
c. Reconciliation of energy accounts with loads
d. Evaluate variation on energy use on a month-to-month basis
e. Identify all practical ECMs and estimate the retrofit cost and energy cost savings for each ECM
f. Include risks and interruption to operations and economic analysis of recommended ECMs
g. Implementation priority and plan
h. Prioritise capital intensive ECMs that require thorough data collection and analysis with an initial estimate of potential cost and savings

<u>Examples of work in Level II Audit</u>

Verify and quantify any spaces that are over cooled using handheld instruments to measure dry bulb temperature and relative humidity.

Verify and quantify any spaces that are having excessive operating hours by checking Building Management System (BMS) if on/off hours are logged reliably. If BMS is not available, operating hours can be verified using loggers that record operating amps of chilled water system or AHUs/FCUs.

Verify and quantify any infiltration of warm and humid outside air by using handheld instruments to measure dry bulb temperature and relative humidity. Use anemometer to verify and quantify the volume of outside air infiltration at openings such as doors or windows by spot measurements.

Verify and quantify any excessive AHU/FCU air change by measuring airflow using an anemometer. Dividing the airflow in CMH by the volume of air conditioned space in m^3 will give the number of air changes per hour.

Verify and quantify any excessive outside air ventilation by measuring the airflow of outside air intake using an anemometer. Dividing the outside air flowrate by the floor area will yield the ventilation rate in L/s per m^2.

Verify and quantify any excessive lighting operating hours.

Verify and quantify any over lit spaces by spot measurements using lux meters.

Verify and quantify chilled water system supply and return chilled water and condenser water temperatures by measuring pipe surface temperature.

Verify and quantify chilled water and condenser water differential pressure using data logger for variable speed pumps or spot measurements for constant speed pumps.

Verify and quantify any cooling tower hot air recirculation by using handheld instruments to measure dry bulb temperature and relative humidity.

Verify and quantify AHU/FCU filter and coil pressure drop by measuring the differential pressure.

Verify and quantify all major sub-system energy flow by spot measurement using power meters that record kW and amps.

Collate all the measurements and analyse the performance by using of tables and charts. Make comparison to design figures and benchmark figures to quantify the level of wastage and efficiency.

<u>Examples of measurement tools for level II audits</u>

- Air temperature and humidity data loggers
- Ampere and power meters
- Anemometers

- Light lux loggers
- Light lux meters
- Water temperature loggers
- Water differential pressure transmitters
- Air differential pressure transmitters
- Digital data loggers

According to SS ISO 50002: 2014, short term metering and logging are usually not needed unless required to fulfil the requirements of the audit scope. The examples of work done in level II audit given above where data logging is required is usually not undertaken unless required to fulfil the requirements of the energy audit scope.

Please refer to Building and Construction Authority's (BCA) Periodic Energy Audit Report Template. A copy of BCA's Periodic Energy Audit Report Template can be found at: https://www.bca.gov.sg/EnvSusLegislation/others/Code_Periodic_Energy_Audit_Bldg_Cool_Sys_2016.pdf

2.3 Level III Audit

A level III audit, sometimes referred to as Investment Grade Audit, provides a detailed analysis of energy usage, the savings that can be made, and the cost of achieving those savings. It may cover the whole facility or may concentrate on capital intensive ECMs that require detailed data collection, financial and engineering analysis. It involves long term, accurate and continuous detailed metering and data logging especially for large and complex systems such as boiler systems, chilled water systems, large ventilation systems, compressed air systems. Level III audits require many high accuracy instruments, complex analysis and are time consuming. Therefore they are typically carried out by specialist ESCOs.

The scope of work for level III energy audit is as follows:
Objective: To measure energy usage/efficiency of major energy consuming systems to a level of uncertainty of +/- 5% for existing systems and for post retrofit performance projection.

a. Follow-up from level II audit and report where available
b. Provide full description of system design, process and operation with detailed drawings and equipment specifications
c. Define facility and system audit process including but not limited to accuracy of overall measurement, uncertainty of instruments, measurement methods, location of instruments, measurement duration and interval
d. Extensive deployment of high accuracy instruments and data loggers to continuously measure, at 1 minute interval, energy use and efficiency over a period of several weeks
e. Deliverables include a detailed energy report with detailed energy use, baseline model, cost, targeted post retrofit energy model, financial analysis and engineering analysis for each recommended ECMs with high level of confidence
f. Detailed investment plan, typically with performance guarantees from ESCO
g. Detailed analysis and description of risks and interruption to operations
h. Recommend refinements to energy policy and energy programme

<u>Example of Level III Energy Audit of Chilled water system</u>

Please refer to Building and Construction Authority's (BCA) Guideline for Health Check Report Annex A for a sample outline of content:
https://www.bca.gov.sg/GreenMark/others/HCEB_AnnexA-AuditReportGuide.pdf

3 Overview of Measurement Instruments

Introduction

In order to quantify energy consumption and evaluate system performance, it is necessary to accurately measure the operating parameters that determine these quantities. Examples of physical operating parameters that have to be measured are electrical power, temperature and flow. Other operating parameters which may have to be measured are pressure, humidity and lighting level. Both reasonably accurate measurement and replicable methodology, followed by good measurement practices are required to identify and quantify these measurements.

ASHRAE Guideline 22-2012 provides information on calibration issues such as ensuring that measurement instruments have their accuracy traceable to the National Institute of Standards and Technology (NIST). Primary standards and no less than third order NIST traceable calibration equipment should be utilised whenever possible. In accordance to Guideline 22, all measurement instruments shall be calibrated before installation unless an in-situ calibration is to be conducted. Manufacturers' calibration data may be sufficient as long as installation conditions match the conditions of calibration. It is recommended that periodic calibration checks and recalibration be required for measurement instruments in order to allow the determination of overall measurement system uncertainty.

Learning Outcomes

Participants will be able to:

i. Understand operating principles and accuracy range of different measurement instruments and installation methods recommended by the instrument manufacturers.
ii. Understand calibration methods for different measurement instruments.

3.1 Power Meter

There are two types of measurement instruments that can be utilised for electrical power measurements. The most common method for sensing electrical alternating current (AC) for energy consumption application is with a current transformer or current transducers (CT), connected to a power meter. Voltage is measured by direct connection to the power source; else some utilise voltmeter or an intermediate device, i.e. potential transducer (PT) to step down the voltage to a safer level. Alternatively, an integrated meter consisting of power meter and CT supplied by the same manufacturer can be utilised to measure electrical power.

Though electrical load is the product of voltage and current, separate voltage and current measurements must not be used, particularly for inductive loads such as motors or magnetic ballasts. For inductive load, it draws inrush current when it is energised and can cause excessive voltages to appear when switched on. Separate voltage and current measurements are unable to measure distorted waveforms. True Root Mean Square (RMS) power digital sampling meters should be used. Nevertheless, it is important that the power measurement system gives an accurate RMS power, including any effects of power factor or any significant harmonic content.

3.1.1 Operating Principles and Accuracy Range

3.1.1.1 Current Transformer

Configuration

Current transformer (CT) converts an alternating current, usually of high value into a proportional current of lower value, which is measurable by standard instruments such as ammeter, power meter and relay. CT used with standard instruments enable current load indication, control demand as well as monitoring with either analogue or digital indicator, known as measuring type current transformer.

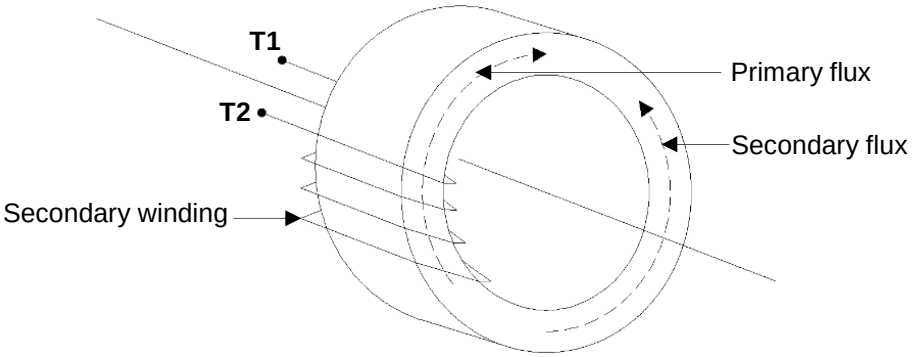


Figure 3.1: *Construction of a current transformer*

A current transformer consists of three basic parts, i.e. primary winding, secondary winding and a magnetic core. The magnetic flux generated by the primary current is balanced or compensated by a current generated in the secondary winding. The secondary winding is wounded around the low loss magnetic core material, so that the flux density is low and the current can be easily stepped down to the required current level. The secondary winding is then connected to the output measuring device.

Depending on the range of current that a current transformer can measure, there are three basic configurations.

a. Ring core CT to measure current from 50 to 5000 amperes with power conductor opening size (i.e. window) range from 1” to 8” diameter.
b. Split core CT to measure current from 100 to 5000 amperes with windows in sizes varying from 1” by 2” to 13” by 30”. The bus bar or load conductor does not need to be disconnected during split core CT installation as one of its ends is removable.

c. Wound primary CT to measure current from 1 to 100 amperes. Screw terminals are provided for the load and secondary conductors since the load passes through the primary windings in the CT.

Installation Method

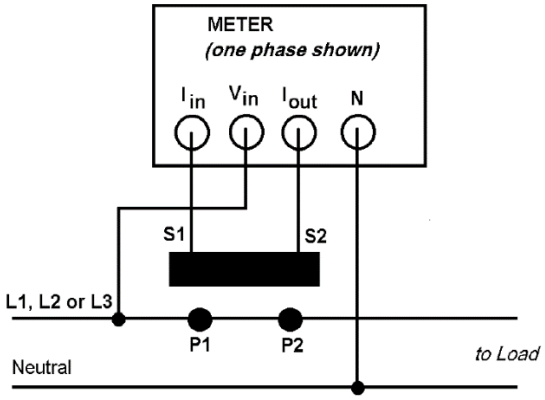


Figure 3.2: *CT polarity – only one phase connected*
(Source: PRI Ltd. 9600-3001-2 Issue E, 2003-2006)

Current transformers are polarised and must be fitted the correct way round. CTs are marked with P1 and P2 to indicate which way it should be fitted around the cable or bus-bar. The side marked P2 must point towards the load. The CT secondary output must be connected to the meter the correct way round, as represented by S1 and S2. Figure 3-2 illustrates CT polarity for only one phase connected.

For three-phase circuit where three CTs are installed, it is a common practice to use one wire as the common secondary lead for all CTs. Figure 3-3 shows connections for a three-phase, four-wire and low voltage CT installation.

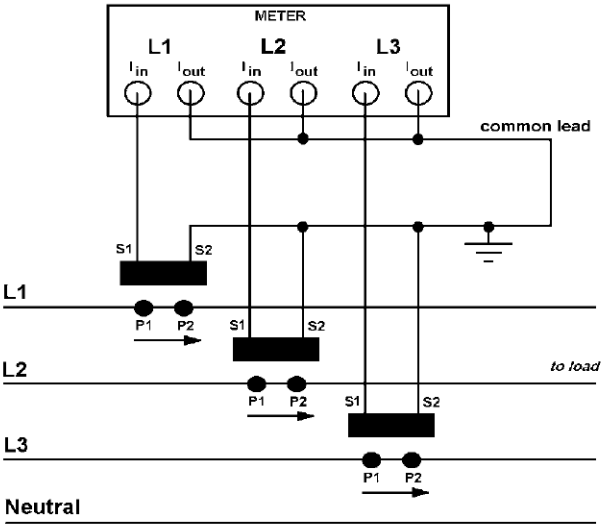


Figure 3.3: *Common CT secondary leads – three phase connected*

(Source: PRI Ltd. 9600-3001-2 Issue E, 2003-2006)

The burden of CT is expressed in volt-amperes (VA). The combined burden of the meter and the cabling must be taken into account before installation. The burden for a meter is fixed, but the burden for cabling increases with length and vice versa.

While it is common that in low voltage installation, CT is grounded at secondary S2 leads to protect against static voltages or insulation failure there only needs to be one ground on the secondary circuit and is usually made at the transformer end as shown in Figure 3-3. For high voltage application, CT must be grounded.

For measuring CT, the secondary current must be directly proportional to the primary current in the range of 10% to 120%. Table 3.1 summarises limits of error for measuring current transformer.

Table 3.1: *Limits of error for measuring current transformer*

(Source: Mun Hean Singapore)

Accuracy Class	**% Current Ratio (Error) at % of Rated Current of**			
	10	**20**	**100**	**120**
0.5	1.0	0.75	0.5	0.5
1.0	2.0	1.5	1.0	1.0

CT is the main component affecting power measurement. The accuracy class of the CT has to be better than that of the power meter in order to achieve the required measurement

accuracy. It is best to match the CT primary current as close to the maximum current in order to maintain measurement instrument accuracy. This is because CT is less accurate at low load compared to full load.

The secondary output of a CT is connected to instruments such as a power meter to ensure that users have access to all power measurements required for control and monitoring purpose, accessible locally or remotely.

Power meters measure true RMS voltage, current, and the power factor and calculate power used by single-phase and balanced or unbalanced three-phase circuits.

Main functions offered by most power meters are listed below:

a. Multi-measurement
   - Current: Instantaneous, maximum, average
   - Voltage and frequency: Instantaneous
   - Power: Instantaneous, maximum, average
   - Power factor: Instantaneous

b. Metering
   - Active energy in kWh
   - Reactive energy in kvarh
   - Hours

c. Harmonic analysis
   - Total harmonic distortion

Table 3.2 shows measurement uncertainties of 2 power meters, which comply with IEC 61557-12 standard.

Table 3.2: *Measurement uncertainties of power meters*

Electrical Characteristic	**Measurement Uncertainty**	
	Brand *X*	**Brand *Y***
Current	0.5%	0.2%
Voltage	0.2%	0.2%
Power factor	±0.002	0.5%
Frequency	±0.01	0.1%
Active energy	IEC 62053-22 Class 0.5S	IEC 62053-22 Class 0.5S
Reactive energy	IEC 62053-23 Class 2	IEC 62053-23 Class 2

3.1.1.2 Integrated Power Meter

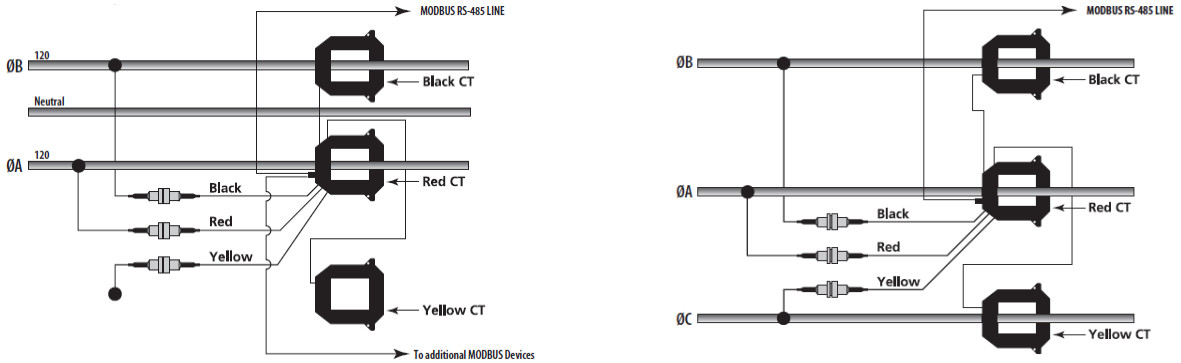


Figure 3.4: *Integrated power meter*)

(Source: Veris ENERCEPT™ H8035/8036)

Figure 3.4 shows an integrated power meter that combines measurement electronics and high accuracy CTs in a single package, i.e. both power meter and CT are supplied by the same supplier. The integrated power meter also offers measurement output for control and monitoring purposes, similar to a typical power meter.

Figures 3.5 (a) and 3.5 (b) illustrate the wiring diagram of integrated power meter mounting for 1-phase and 3-phase electrical power measurements respectively.



(a) (b)

Figure 3.5: *(a) 1-phase and (b) 3-phase power measurement*

(Source: Veris ENERCEPT™ H8035/8036)

For integrated power meter, the system uncertainty is ±1% of reading from 10% to 100% of the rated current of CTs, accomplished by matching the CTs with a meter and calibrating them as a system.

3.1.1.3 Determination of Power Based on RMS Current

The 'Root Mean Square' (RMS) magnitude of an alternating current (AC) is the value of equivalent direct current (DC) that would produce the same amount of heat in a fixed resistive load.

The most common graphical representation of AC current is a sine wave as the amplitude of the sine wave continuously changes over the wave period (one complete cycle). At any given point in time, a current measurement would not be the same. There are two methods of measuring AC current:

a. To take current measurements at increments across one complete cycle and average them together. This would give an average value of the current. If the current is a perfect sine wave, mathematically, the average value is always 0.636 times the value of the peak amplitude.
b. To measure current based on the current's ability to perform work when applied to a resistive load. The laws of physics state that when current passes through a resistive load, it dissipates energy in the form of heat, mechanical motion, radiation or other forms of energy. If the resistive load is a heating element and the resistive load stays constant, then the laws of physics state that the heat produced is directly proportional to the square of current passing through the load. Therefore, if heat is measured, current is also known.

Mathematically, the relationship between heat and current is such that the power consumed, *P* or heat dissipated, *Q* is proportional to the square of the current, *I* applied to a resistance, *R*.

$$P \text{ or } Q = I^2 \times R$$

If the current is continuously changing, as in AC current, the heat dissipated is proportional to the average (or mean) of the square of the current applied to a resistance:

$$P \text{ or } Q = \frac{I^2 \times R}{n}$$

where *n* is the number of measurement taken.

Using algebra, the above formula can be rewritten to read:

$$I = \sqrt{\frac{P \text{ or } Q}{R}}$$

And the above is called the Root Mean Square current or RMS current.

The RMS current will always be 0.707 times the peak current for AC currents that are graphically represented by a perfect sine wave. Therefore, the RMS current can be calculated by multiplying peak measurements by 0.707 if the current is a perfect sine wave. However, perfect sine waves rarely occur in most applications because resistive loads in most applications are not linear, which results in unpredictable or variable current requirements.

In order to get a True RMS measurement, the heat dissipated by a constant resistive load can be measured and used in the calculations above.

There are two calculation methods to determine the power measurement of a 3-phase system.

a. Calculate the power for each phase and sum it up
   $P_1 = V_{1\text{-}N} \times I_{1rms} \times \text{PF}$
   $P_2 = V_{2\text{-}N} \times I_{2rms} \times \text{PF}$
   $P_3 = V_{3\text{-}N} \times I_{3rms} \times \text{PF}$
   $P_{total} = P_1 + P_2 + P_3$
   where $V_{1\text{-}N} = 240$ V
b. Calculate the total power directly
   P_{total} = 1.732 x Average $V_{L\text{-}L}$ x Average I_{rms} x PF
   where $V_{L\text{-}L} = 415$ V

Example 3.1

Consider a balanced 3-phase load consuming 60 A in each phase at a power factor of 0.86 and voltage of 415 V ($V_{L\text{-}L}$) and 240 V ($V_{L\text{-}N}$):

Method 1

$P_1 = V_{1\text{-}N} \times I_{1rms} \times \text{PF} = 240 \times 60 \times 0.86 / 1000 = 12.38$ kW

$P_{total} = P_1 + P_2 + P_3 = 37.1$ kW

Method 2

P_{total} = 1.732 x Average $V_{L\text{-}L}$ x Average I_{rms} x PF

= 1.732 x 415 x 60 x 0.86 / 1000

= 37.1 kW

Overall, among the current calculation methods mentioned above i.e. measurement of average current, multiplication of current peaks by 0.707 to get an RMS current or

measurement of heat from a resistor and calculate a True RMS current, the most accurate way to calculate current shall be a True RMS method. Average current values are often 40% less than True RMS values and that could mean the difference between blown circuit breakers, malfunctioning motors, or worst case, potential fire hazards.

3.1.2 Calibration of Power Meter

Singapore Standard SS591: 2013 Code of Practice for Long Term Measurement of Central Chilled Water System Energy Efficiency specifies that the maximum allowable uncertainty for power measurement under laboratory conditions shall be ±2%. It is recommended to have at least a minimum accuracy class of 1 for the power meters and an accuracy class of 0.5 for the current transformers. The uncertainty of the power measurement system shall take into consideration the uncertainties of the power meter and any associated voltage and current transformer.

Presently, type test reports from power meter manufacturers are acceptable. It is highly recommended to use verified power meters, with individual test certificates prior to the installation of any power meter(s) and current transformer(s) in order to achieve the overall chilled water system measurement accuracy.

Calibration of instruments that measure power is no different from any other calibration. The instrument under test is supplied with a known quantity of the parameter being calibrated, and the instrument is interrogated in order to ascertain the value of the parameter that it has measured. This value is then compared with the quantity supplied and the measurement error is calculated. Calibrations are typically performed by using a reference measurement technique. The meter shall conform to ANSI C12.1 metering standards.

3.2 Temperature Sensor

Temperature sensors are deployed for both water and air applications. Water temperature sensors can be immersion or cable type; while air temperature sensors can be probe type. Temperature measurements are useful in determining overall chilled water system performance and hence optimising system operating parameters. These temperature measurements are:

a. Chilled water supply and return temperature measurements to determine cooling capacity;
b. Condenser water supply and return temperature, outdoor dry bulb, evaporator and condenser refrigeration temperatures are important to provide chiller operating and optimising information;
c. Supply air and return air temperature, room temperature to provide air side components (i.e. air handling units and fan coil units) operating and optimising information for human comfort.

As outlined in ASHRAE Guidelines 22-2012, all temperature instrumentation shall be installed close to the inlet of temperature-changing devices such as chillers and cooling towers but as far away from outlet as possible to ensure any temperature stratification in the outflow is well-mixed. The most commonly used temperature measurement devices are thermocouples, resistance temperature detectors (RTDs) and thermistors.

a. Thermocouples

   Thermocouples measure temperature using two dissimilar metals, welded together at one end. Example of metals are Copper (Cu)/Constantan, Iron (Fe)/Constantan, etc. A small voltage is generated as a function of temperature at the welding point so called “junction”.
b. Resistance temperature detectors (RTDs)

   These are common sensors for air and water temperature measurements. It measures the change in electrical resistance in special materials.
c. Thermistors

   These are semiconductor temperature sensors consisting of an oxide of manganese, nickel, cobalt or one of several other types of materials. Both RTDs and thermistors measure change in electrical resistance. However, thermistors have a large resistance change with temperature compared to RTDs. Thermistors are not interchangeable and their temperature-resistance relationship is non-linear.

Each temperature sensor has its advantages and disadvantages based on the application needs. Table 3.3 shows the comparison of most common temperature transducers.

Table 3.3: *Common temperature transducers*

(Source: Data Acquisition Fundamentals by Measurement Computing, Inc.)

Description	Thermocouples	RTDs	Thermistors
Temperature range	Best (-200°C to 1700°C)	Better (-200°C to 800°C)	Good (-55°C to 300°C)
Accuracy	Good	Better	Best
Cost	Low	High	Medium
Sensitivity	Good	Better	Best

From the above list, the least accurate temperature sensor is thermocouples although they are inexpensive. RTDs are more expensive than thermocouples, but offer greater accuracy and stability. Thermistors are less expensive than RTDs, more accurate than RTDs and thermocouples, and offer excellent sensitivity.

3.2.1 Operating Principles and Accuracy Range

3.2.1.1 Thermocouple

Configuration

Two dissimilar metals of thermocouple are joined together at one end, called the measurement ("hot") junction; while the other end called reference ("cold") junction is connected to the signal conditioning circuitry, which is typically made of copper.

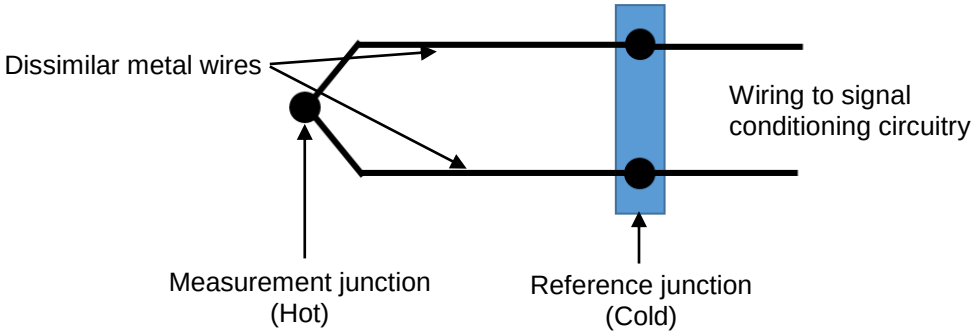


Figure 3.6: *Thermocouple*

The measurement junction produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as Seebeck voltage. The voltage is non-linear with respect to temperature despite the voltage being approximately linear for small changes in temperature.

$$dV = S * dT$$

where dV is the change in voltage, S is the Seebeck coefficient and dT is the change in temperature. There are several types of thermocouples designated by capital letters as an indication of its composition according to American National Standards Institute (ANSI) convention.

Table 3.4 lists the Seebeck coefficient of various types of thermocouples.

Table 3.4: *Seebeck coefficient of various types of thermocouples at 25^{o}C*

Thermocouple Types	Materials	Seebeck Coefficient (μV/^{o}C)
E	Nickel-Chromium/Constantan	61
J	Iron/Constantan	52
K	Nickel-Chromium/Nickel-Alumel	41
N	Nicrosil/Nisil	27
R	Platinum Rhodium 13%/Platinum	9
S	Platinum Rhodium 10%/Platinum	6
T	Copper/Constantan	41

It is not easy to transform the voltage generated by a thermocouple into an accurate temperature reading. One of the reasons is that the voltage signal is small and the temperature-voltage relationship is non-linear. Nevertheless, the most common thermocouple types are *J*, *K*, and *T*. At room temperature, their voltage varies at 52 μV/°C, 41 μV/°C, and 41 μV/°C, respectively.

It is also noted that a thermocouple is often enclosed in a protective sheath to isolate it from the local atmosphere and hence reduce the effects of corrosion. Stainless steel is the most common sheath material and is relatively corrosion resistant and cost effective.

Table 3.5 outlines the advantages and disadvantages of using thermocouples in temperature measurement.

Table 3.5: *Advantages and disadvantages of thermocouples*

Advantages	Disadvantages
• Wide temperature range from -200^{o}C to +2500^{o}C depending on the type of metal wires used	• Complex signal conditioning as substantial signal conditioning is required to convert thermocouple voltage into useful temperature reading
• A rugged device and is suitable for hazardous environment application	• Only as accurate as the reference junction temperature can be measured, typically within 1^{o}C to 2^{o}C

Advantages	Disadvantages
• Low thermal capacity and responds rapidly to temperature changes if the sensing junction is exposed	• Prone to corrosion due to two dissimilar metals and results in deteriorating accuracy
• Require no excitation power and is not prone to self-heating	• Susceptibility to noise especially when measuring microvolt-level, noise from electrical and magnetic fields can be a problem.

Measurement Method

To measure a thermocouple Seebeck voltage, thermocouple shall not be connected directly to a voltmeter or other measurement system as it creates additional thermoelectric circuits. With reference to the operating principle of a thermocouple, the thermocouple is only able to indicate the temperature attained by its measuring junction, with a fixed or known reference junction. Therefore, it is necessary to ensure that the measuring junction is at the same temperature as the medium to be measured to achieve the accuracy desired. Factors that influence measuring junction temperature of a particular installation are:-

a. Surrounding temperature
b. Velocity and properties of the fluid
c. Emissivity of the exposed surface
d. Thermal conductivity of thermocouple and well materials
e. Ratio of heat transfer area

In addition, thermocouples can produce a variety of errors when not installed properly. Dissimilar wires of thermocouples shall be soldered or welded at the junction instead of twisted together to form a junction. Thermocouples can become uncalibrated and measure the wrong temperature when the physical wire is modified and not meeting the NIST standards.

Measuring Accuracy

Table 3.6 compares standard accuracy of different types of thermocouples. Standard limits of error means that these thermocouples use standard “thermocouple grade” wire and are more common and less expensive. Thermocouple grade wire is used to manufacture thermocouple probes. It is normally used for the junction and inside the stem sheath because thermocouple grade wire has an accuracy specification. Each type of thermocouple grade wire consists of different wire insulation and conductor material properties.

Table 3.6: *Measuring accuracy of different types of thermocouples*

Thermocouple Types	Standard Accuracy
E	±1.7°C
J	±2.2°C
K	±2.2°C
N	±2.2°C
R	±1.5°C
S	±1.5°C
T	±1.0°C

Although thermocouple wire is manufactured to NIST specifications, the wire accuracy can be improved when it is calibrated onsite against a known temperature standard.

3.2.1.2 Resistance Temperature Detectors (RTDs)

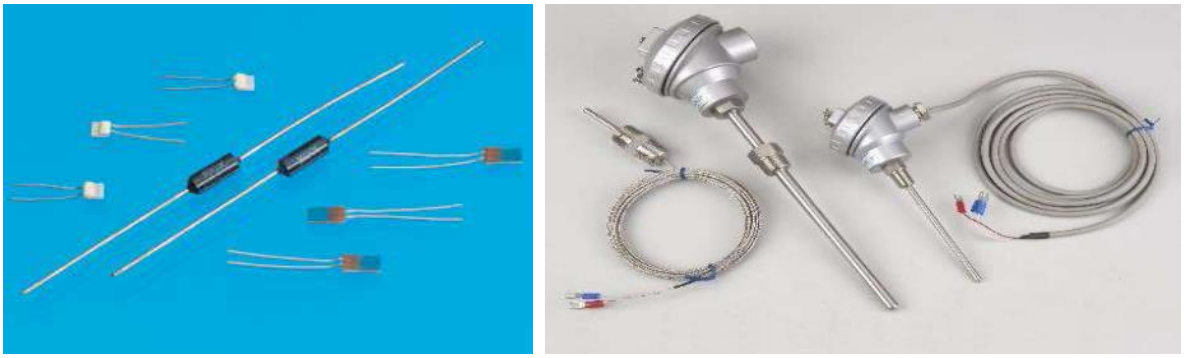


Figure 3.7: *Resistance temperature detectors*

A RTD is a temperature sensor that contains an electrical resistance source which resistance value changes with respect to its temperature. RTD consists of metals with a high positive temperature coefficient of resistance. This means that resistance increases with temperature.

Configuration

The most common materials used in the construction of RTDs are platinum, nickel and copper; platinum being the most commonly used material. Different materials used provide a different relationship between resistance and temperature. By supplying RTD with a constant current and measuring the resulting voltage across the resistor, the RTD's resistance can be calculated and the temperature can be determined. In addition to different materials, there are two major configurations of RTDs i.e. thin film and wire wound.

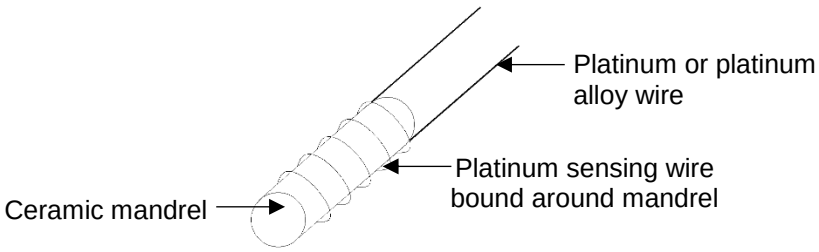


Figure 3.8: *Typical wire wound element*

Figure 3.8 shows wire wound configuration of RTD. An inner coil construction consists of a resistive coil running through a hole in a ceramic insulator, whereas the outer wound construction involves the winding of the resistive material around a ceramic or glass cylinder, which is then insulated.

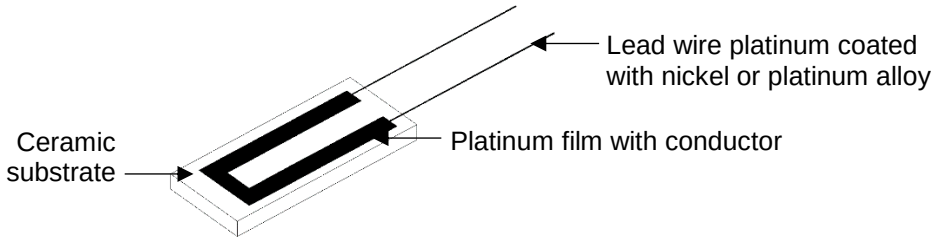


Figure 3.9: *Film type element*

An alternative to the wire-wound RTD is the thin-film element. It consists of a very thin layer of resistive material, which is deposited onto a ceramic substrate. A resistive meander is then etched onto the sensor and then laser trimmed to the desired resistance value. Thin film elements can attain higher resistances with less metal and hence it is less expensive than the equivalent wire-wound element.

Table 3.7 outlines the advantages and disadvantages of using a RTD.

Table 3.7: *Advantages and disadvantages of RTD*

Advantages	Disadvantages
• Linearity over a wide operating range	• Low sensitivity and can be affected by contact resistance and vibration
• Higher temperature operation	• Requires no point sensing and is not suitable to applications requiring fast response or small area temperature sensing
• Better stability at high temperature	• Higher cost than other temperature sensor types

Measurement Method

As RTD is a resistive device, a current must be driven through the device and the resulting voltage is monitored. Depending on the nominal resistance of the RTD, different supply currents can be used. To reduce self-heating on the sensor, the supply current shall be kept low and in general approximately 1 mA or less of current is supplied. However, any lead wires that connect to the measurement system will add error to the readings.

There are several techniques of measuring temperature with RTD. An RTD can be connected in a two, three, or four-wire configuration.

a. Two-wire method

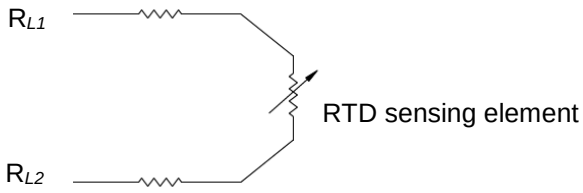


Figure 3.10: *Two-wire configuration*

Two-wire method is the simplest configuration. The measured resistance is the summation of wire and RTD sensing element. This is the least accurate of the 3 techniques since there is no way of eliminating the lead wire resistance from the sensing element. This method is mostly used with short lead wires or where temperature measurement accuracy is not required.

b. Three-wire method

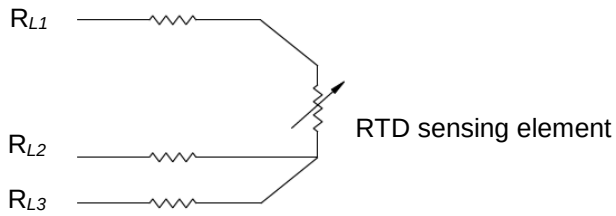


Figure 3.11: *Three-wire configuration*

Three-wire method removes the average lead wire resistance from the RTD sensing element. This requires a three-wire compensating measurement unit or measuring the contribution from the third wire and subtracting it from the overall measurement.

c. Four-wire method

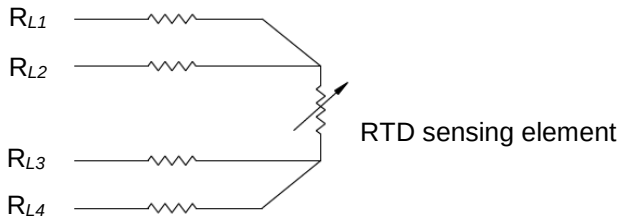


Figure 3.12: *Four-wire configuration*

In four-wire method, the current is sourced on one set of lead wires while voltage is sensed on another set of lead wires. The voltage sensed at the RTD sensing element is different from the current source. It means that the sensing element test lead resistance is not a part of the measurement. This is a more accurate technique for measuring resistance of RTD as it completely eliminates the lead wire resistance.

In order to calculate RTD resistance, the Callendar-Van Dusen equation is used.

$$R_T = Ro + Ro\,\alpha\left[T - \partial\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) - \beta\left(\frac{T}{100} - 1\right)\left(\frac{T^3}{100}\right)\right]$$

The Callendar-Van Dusen equation is commonly used to approximate RTD curve i.e.

$$R_t = R_0[1 + At + Bt^2 + C(t - 100)^3]$$

Where R_t is the resistance of RTD at temperature = t, R_0 is the resistance of RTD at 0°C, A, B and C are the Callendar-Van Dusen coefficients (Table 3.8) and t is the temperature in °C.

Table 3.8: *Callendar-Van Dusen coefficients corresponding to common RTDs*

Standard	Temperature Coefficient (α)	*A*	*B*	*C*
DIN43760	0.003850	3.9080×10^{-3}	-5.8019×10^{-7}	-4.2735×10^{-12}
American	0.003911	3.9692×10^{-3}	-5.8495×10^{-7}	-4.2325×10^{-12}
ITS-90	0.003926	3.9848×10^{-3}	-5.8700×10^{-7}	-4.0000×10^{-12}

The temperature coefficient, α, differs between RTD curves. Although different manufacturers may specify temperature coefficient differently, it is commonly defined as the change in RTD resistance from 0°C to 100°C, divided by the resistance at 0°C, divided by 100°C:

$$\alpha\ (\Omega/\Omega/^oC) = (R_{100} - R_0)/(R_0 \times 100^oC)$$

where R_{100} is the resistance of the RTD at 100°C and R_0 is the resistance of the RTD at 0°C.

For example, in a two-wire method, a lead resistance of 0.2 Ω in each wire, *RL*, adds a 0.4 Ω error to the resistance measurement. Therefore, for a platinum RTD with α = 0.00385, the resistance equals a 0.4 Ω/(0.385 Ω/°C) = 1.0°C error.

Measuring Accuracy

RTDs are very accurate and nearly linear over typical temperature ranges. With proper calibration, uncertainties of better than 0.1°C can be achieved.

Accuracy classes for platinum RTDs are defined by IEC 751 and are typically listed as either DIN Class A or DIN Class B.

Table 3.9: *Temperature accuracies according to IEC 751 and DIN EN 60751*

Temperature (°C)	Class A Limit	Class B Limit
-200	±0.55°C	±1.3°C
-100	±0.35°C	±0.8°C
0	±0.15°C	±0.3°C
100	±0.35°C	±0.8°C
200	±0.55°C	±1.3°C
300	±0.75°C	±1.8°C
400	±0.95°C	±2.3°C
500	±1.15°C	±2.8°C
600	±1.35°C	±3.3°C
650	±1.45°C	±3.6°C

Alternatively, the tolerances for uncalibrated platinum resistance elements are determined by the following equations.

Class A: $\Delta t = \pm(0.15^oC + 0.002|t|)$

Class B: $\Delta t = \pm(0.3^oC + 0.005|t|)$

where | *t* | is the absolute value of temperature in °C.

3.2.1.3 Thermistors

Thermistors are resistors and their resistance changes with the temperature. Depending on the material characteristics, thermistors can exhibit a positive or negative temperature coefficient (PTC or NTC). Both NTC and PTC thermistors provide variable resistance based on temperature. As temperature increases, the resistance drops from high to low and allows current to pass through in a NTC thermistor. For PTC thermistors, the resistance of the metals increases with temperature. They are typically used as heating elements or in circuit protection applications, as the increasing resistance limits current which in turn prevents thermal runaway. For temperature measurement in air-conditioning application, more discussion of NTC thermistors is in the next section.

Configuration

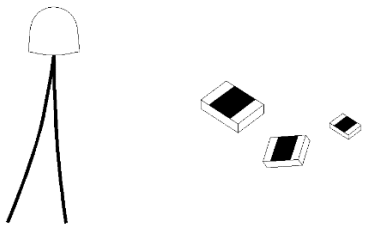


Figure 3.13: *NTC thermistors*

NTC thermistors are made using a mixture of metals and metal oxide materials such as manganese, nickel, cobalt and copper. These materials are oxidised through a chemical reaction, ground into fine powder and compressed into the required shape at an elevated temperature. NTC thermistors are available in various shapes like disc, rod, washer, bead etc. They are of small size and can be connected to the circuit easily.

Glass-coated beads feature excellent long-term stability and reliability for operation at temperatures up to 300°C. The relatively small size of glass bead thermistors provides a quick response to temperature changes. However, the small size of glass bead thermistors might cause difficulties during assembly and have the effect of limiting their power dissipation. It is also more difficult and more expensive to produce glass beads with close tolerances and interchangeability. Individual calibration and R/T characterization, resistor network padding, or use of matched pairs are among the methods used to achieve interchangeability.

Chip and disc thermistors are known for its tight tolerances and interchangeability at a relatively low cost compared to bead thermistors. Larger size of chip and disc thermistors permit power dissipation higher than that of beads, although at some expense of response times.

Measurement Method

Thermistor resistance is determined by the manufacturer by applying a constant current through the thermistor and then measuring the voltage drop that occurs across the thermistor. By applying Ohm's Law, the resistance is determined.

$$R = V/I$$

where *R* is the resistance, *V* is the voltage and *I* is the supplied current.

Next, the Steinhart-Hart equation is used to calculate the temperature.

$$\frac{1}{T} = A + B(\ln R) + C(\ln R)^3$$

where *T* is the temperature in Kelvin and *R* is the resistance at temperature *T*. Coefficients *A*, *B*, and *C* are derived by calibrating at three temperature points at three temperature controlled medium and then solving the three simultaneous equations. The uncertainty associated with the use of the Steinhart-Hart equation is less than ±0.005°C for 50°C temperature spans within the 0°C-260°C range. Table 3.10 shows the *A*, *B* and *C* coefficients for two different types of NTC thermistors from two different thermistor manufacturers.

Table 3.10: *Variability of A, B, and C coefficients for different types of NTC thermistors*

	Thermistor Brand *A*		**Thermistor Brand *B***	
Coefficient/Thermistor Type	**10k**	**30k**	**10k**	**30k**
A	9.331754E-4	1.028444E-3	9.354E-04	1.0295E-03
B	2.213978E-4	2.392435E-4	2.211E-04	2.391E-04
C	1.263817E-7	1.562216E-7	1.275E-07	1.568E-07

Figure 3.14 illustrates a typical temperature measurement chain during energy measurement and appraisal.

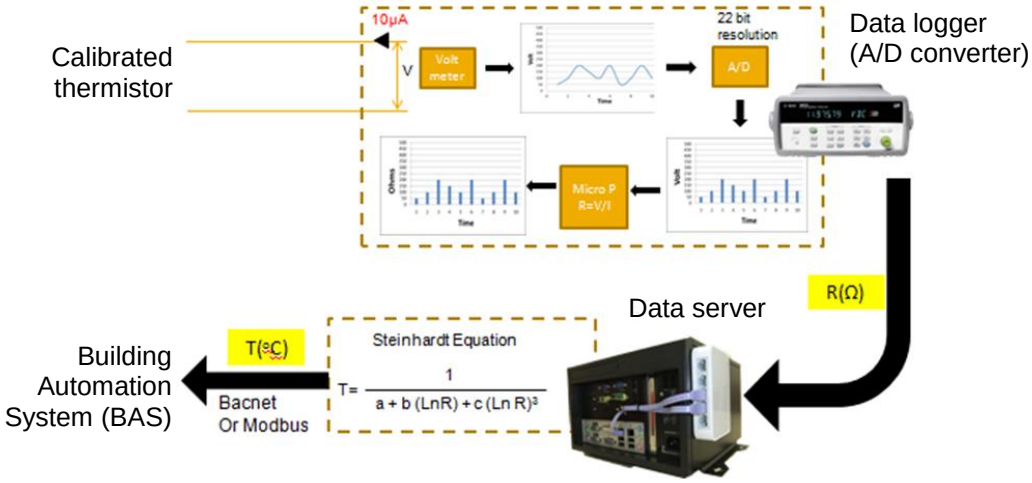


Figure 3.14: *Typical temperature measurement chain*

The practical lower temperature limit is reached when the voltage exceeds the maximum input voltage of the analogue to digital (A/D) converter i.e. data logger. As the NTC thermistor temperature increases, its resistance decreases, and so does its sensitivity to temperature change. Since the system A/D converter has a fixed resolution, it means that temperature measurement resolution decreases with increasing temperature.

In addition, as thermistors are operated at temperatures where they exhibit high resistances of hundreds or thousands of ohms, simple two-wire measurement method is sufficient. Therefore, thermistors are suitable for temperature measurement via long wire cable because the resistance of the long wire is not significant compared to the relatively high resistance of the thermistors.

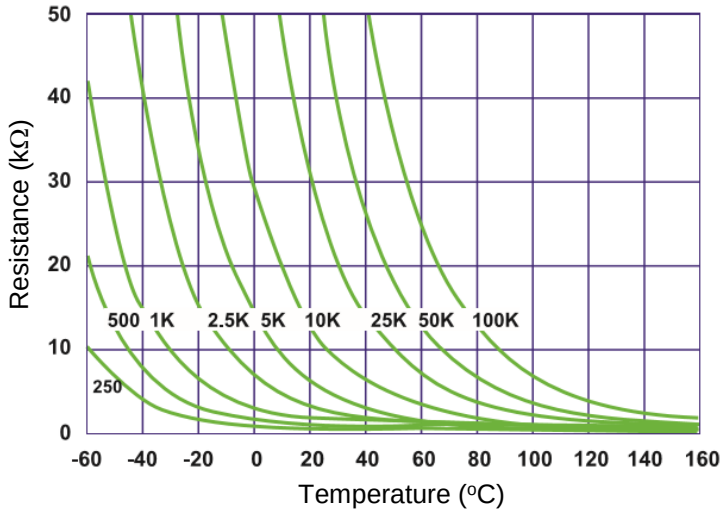


Figure 3.15: *Plot of Ω versus °C range for different types of NTC thermistors*
(Source: This copyrighted material is being used with the permission of Electrical Apparatus Service Association, Inc. (EASA); all rights reserved.)

Nevertheless, resistance versus temperature data of thermistors and the Steinhart-Hart equation are used for determining the resistance of a thermistor, which reference was made to “ideal” measurement conditions for determining the resistance of the thermistor. There are several factors listed below that affect resistance measurement of a thermistor.

a. Self-heating effect of thermistors

   The heating effect in turn causes the resistance of the thermistor to decrease. To obtain a resistance reading from the thermistor that accurately represents the actual temperature, it is critical that the power levels associated with the measurement are low enough not to cause appreciable self-heating. Self-heating effect can by quantified by using the concept of "Zero-power resistance characteristic."

b. Zero-power resistance characteristic

   In practical terms, a thermistor is generally considered to be dissipating zero-power when the current through it is less than 100 μA.

   The measured resistance value of a thermistor in a medium is affected by the thermal characteristics of the system which comprises the thermistor coupled with the medium being measured.

c. Thermal time constant

   The thermal time constant for a thermistor is the time required for a thermistor to change its body temperature by 63.2% of a specific temperature span when the measurements are made under zero-power resistance conditions in thermally stable environments. This dynamic thermal response of a thermistor must be considered.

d. Thermal dissipation constant

   The value of resistance of a thermistor that is measured in a physical system depends on the power dissipated in the thermistor due to the measurement method and also on the thermal characteristics of a dynamic temperature system. It is important to consider both effects in measuring temperature using thermistors. The thermal dissipation constant of a thermistor is defined as the power required to raise the thermistor's body temperature by 1^{o}C in a particular measurement medium, expressed in units of mW/^{o}C.

Measurement Accuracy

Temperature measurement accuracy of thermistor is limited by the ability to measure voltage drop across it and current flow. The thermistor itself can be calibrated to an uncertainty of 0.001^{o}C. The calibration must be performed at a minimum of three temperatures to enable an adequate curve fit for the temperature-resistance curve. With this procedure, system measurement uncertainties of better than 0.1^{o}C can be obtained. Thermistor resistance measurements must be made at precisely controlled temperature while applying essentially zero-power to assure measurement accuracy.

In the thermistor application, in order to match the required measurement accuracy, every individual component's accuracy within the measurement circuit shall be taken into the consideration. Measurement errors due to the following components affect the measurement accuracy of a thermistor.

a. Signal measurement (data logger: analogue-to-digital converter)
b. Sensor bias circuit (reference resistor)
c. Actual sensor (thermistor)
d. Voltage-to-temperature conversion (thermistor component)

Besides, accuracy of temperature measurement, different types of temperature sensors are also highly dependent on the installation method and conditions in which the sensors are exposed to. For example, use of thermally conductive paste, silicone rubber or similar material will assist to speed up the response time and minimise conduction errors.

A comparison of temperature sensor characteristics among thermocouple, RTD and NTC thermistor is outlined in Table 3.11.

Table 3.11: *Comparison of temperature sensor characteristics*

Description	Thermocouple	Platinum RTD	NTC Thermistor
Working principle	Conversion of voltage measurement at a junction of two different types of metals to temperature.	Prediction of change in electrical resistance of some materials with respect to temperature changes. Most commonly used material is platinum.	Prediction of change in electrical resistance with temperature. Made from certain metal oxides.
Type of sensor	Thermoelectric	Platinum wire-wounded or metal film	Ceramic (metal-oxide spinel)
Typical temperature range	-200 to +1750^{o}C	-200 to +650^{o}C	-100 to +325^{o}C
Typical accuracy	0.5 to 5.0^{o}C	0.1 to 1.0^{o}C	0.05 to 1.5^{o}C
Long term stability at 100^{o}C	Variable and several types are very prone to aging	0.05^{o}C/year (film) 0.002^{o}C/year (wire)	0.2^{o}C/year (epoxy) 0.02^{o}C/year (glass)
Linearity	Most types non-linear	Fairly linear	Exponential
Power required	Self-powered	Constant voltage or current	Constant voltage or current
Response time	Fast 0.10 to 10s	Generally slow 1 to 50s	Fast 0.12 to 10s
Lead resistance effects	None over short run. Extension cables required	3- to 4- wire configurations required	Low resistance parts only
Cost	Low	Low (Film) High (Wire-wound)	Low to moderate

3.2.2 Calibration of Temperature Sensor

3.2.2.1 The International Temperature Scale (ITS-90)

The International Temperature Scale of 1990 (ITS-90) is an equipment calibration standard for making measurements on the Kelvin and Celsius temperature scales. ITS–90 is an approximation of the thermodynamic temperature scale that facilitates the comparability and compatibility of temperature measurements internationally. It offers defined calibration points ranging from 0.65 K to approximately 1358 K (−272.5°C to 1085°C) and is subdivided into multiple temperature ranges.

Temperatures measured with equipment calibrated per ITS–90 may be expressed using any temperature scale such as Celsius and Kelvin (Fahrenheit). A practical effect of ITS–90 is the triple points and the freezing/melting points of its thirteen chemical elements are precisely known for all temperature measurements calibrated per ITS-90 since these thirteen values are fixed by its definition.

In calibration of temperature sensor, the common practice is to use secondary thermometers and calibrate them to an internationally recognised temperature scale based on primary thermometers and fixed points. A thermometer is named as primary thermometer if an equation state can be written explicitly without introducing any unknown. For example, gas thermometer, acoustic thermometer, noise thermometer and total radiation thermometer. A secondary thermometer has an output that must be calibrated against defined fixed temperature points. For example, a platinum resistance temperature detector (RTD) is based on the change in resistance of a platinum wire with temperature.

The International Temperature Scale of 1990 defines temperature by

a. defining fixed points of temperature
b. interpolating thermometer and interpolating equations, a sensor with an output depending on temperature

<u>Defined Fixed Points</u>

The ITS–90 uses numerous defined points, all of which are based on various thermodynamic equilibrium states of fourteen pure chemical elements and one compound (water). Most of the defined points are based on a phase transition.

Interpolating Instruments and Equations

The ITS-90 defines three types of interpolating instruments:

a. Interpolating constant volume gas thermometer (ICVGT) for temperature range from 3 K to 24.5561 K;
b. Standard platinum resistance thermometer (SPRT) for temperature interval from 13.8033 K to 1234.94 K;
c. Radiation thermometer for temperature above silver freezing point (1234.94 K).

3.2.2.2 Platinum Resistance Thermometer (PRT)

A platinum resistance thermometer (PRT) is a thermometer constructed from a high purity platinum element (wire-wound coil or thin film) placed in a tube of metal or glass and sealed with an inert atmosphere and/or mineral insulator. Two, three, or four leads are connected to the element and are used to provide for the measurement of the electrical resistance of the element. PRTs are suitable for use over a wide temperature range.

Standard Platinum Resistance Thermometers

Standard Platinum Resistance Thermometers (SPRT) are the most accurate and stable instruments available for this purpose. The different resistance values and different sheath materials of SPRT are intended for different temperature ranges. A typical quartz sheathed 25Ω SPRT will have a temperature range of –200°C to 660°C and with a high quality calibration will have calibration uncertainties from 0.001°C to 0.010°C.

Industrial Platinum Resistance Thermometers (IPRTs)

These instruments are not as accurate as SPRTs but they are generally more rugged and easier to work with. Not all designs perform to the level required for use as a reference. IPRTs have been limited to a temperature range of –200°C to 420°C but a new type has been introduced which has extended the upper limit to 1000°C. The calibration uncertainties range from 0.010°C to 0.025°C.

The relationship between the resistance of the platinum resistance thermometer under calibration and temperature measured with a reference thermometer is described with an interpolation equation. This equation is determined using the least square method on the data acquired during the comparison. The Callendarvan-Van Duesen equation is generally accepted as interpolation equation for IPRTs, rather than for SPRTs. It is the most common method to convert resistance to temperature. The equation is below:

$$RTD = R_0[1 + At + Bt^2 + C(t - 100)^3]$$

where RTD is the RTD resistance at temperature t, R_0 is the RTD resistance at 0ºC and A, B and C are Callendar-Van Duesen coefficients.

3.2.2.3 Calibration Equipment

Comparison calibration is performed by measurement of the resistance of the instrument under calibration while it is exposed to a temperature. Fundamentally, four items are required and they are as follows:

a. Reference standard
b. Data acquisition for the reference standard
c. Data acquisition for the instrument under calibration
d. Temperature source

Data Acquisition

When calibrating PRTs against a reference PRT or SPRT, the technical requirements for the output of the PRT are the same for both the instruments under calibration and the reference. One has to ensure that the readout has a resistance range appropriate for the reference probe and instruments under calibration for which it is intended. For example, over the range of -80°C to 80°C, a 25Ω SPRT will vary in resistance from approximately 17Ω to 32Ω; while a 100Ω PRT from approximately 68Ω to 130Ω. In addition, one also has to ensure that the readout is using the proper source current. Too much source current will result in excessive self-heating and incorrect calibration.

Temperature Source

The most common temperature sources in meteorological applications for PRT calibration are calibration baths for waterproof instruments and climatic chambers for non-waterproof instruments. A calibration bath/chamber cannot be considered as completely stable in time and homogeneous all over its volume, especially when temperature calibrations by comparison are performed at the best level of uncertainty. One has to consider the homogeneity and stability of a calibration bath.

3.2.2.4 Typical Set-up for Temperature Sensor Calibration

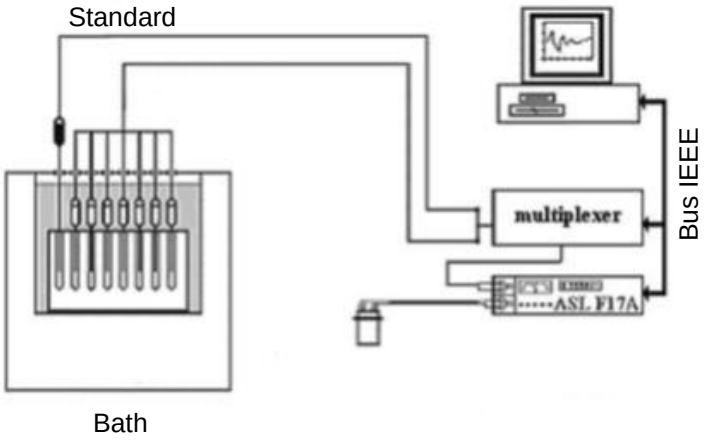


Figure 3.16: *Typical set-up for resistance thermometer calibration*
(Source: WMO/TD-No. 1543, 2010)

Figure 3.16 illustrates a typical set-up for resistance thermometer calibration such as RTD and thermistor. For routine calibrations of 4-wires resistance thermometers, a calibration bath is commonly used. The calibration is made by comparing to the standard from -40°C to 40°C. At each level of temperature, 100 measurements are made for every 5 seconds with a bridge and multiplexer. The common measurement current is 1 mA.

3.3 Water Flow Meter

There are many different types of flow meters available for liquid piping systems. In general, flow meters can be classified according to its operating principle as shown in Table 3-12.

Table 3.12: *Operating characteristic of different types of flow meters*

Differential Pressure	**Positive Displacement**	**Velocity**	**Mass**	**Open-Channel**
Orifice plate	Reciprocating piston	Turbine	Coriolis	Weir
Venturi tube	Oval gear	Vortex shedding	Thermal	Flume
Flow nozzle	Rotary vane	Electromagnetic		
Pitot tube		Ultrasonic		

The following key factors are critical in determining the right type of flow meter for one specific application.

a. Fluid characteristic (phase, viscosity and turbidity)
b. Flow profile (laminar, transitional, turbulent, etc.)
c. Flow measurement range

Other additional considerations such as mechanical restrictions and output-connectivity options also affect flow meter selection criteria. The overall accuracy of a flow meter to some extent is dependent on the actual circumstances of the application; while the effects of pressure, fluid temperature and dynamic influences can substantially change the measurement taken.

With most liquid flow measurement instruments, the flow rate is determined inferentially by measuring the liquid's velocity or the change in kinetic energy. Velocity depends on the pressure differential that is forcing the liquid through a pipe. Because the pipe's cross-sectional area is known and remains constant, the average velocity is an indication of the flow rate. The basic relationship for determining the liquid's flow rate in such cases is:

$$Q = v \times A$$

where Q is the liquid flow rate through the pipe, v is the average velocity of the flow and A is the cross sectional area of the pipe.

Other factors that affect liquid flow rate include the liquid's viscosity and density, and the friction of the liquid in contact with the pipe.

Alternatively, direct measurements of liquid flows can be made with positive-displacement flowmeters. These units divide the liquid into specific increments and move it on. The total flow is an accumulation of the measured increments, which can be counted by mechanical or electronic techniques.

Further description on operating principles and accuracy of electromagnetic flow meter, ultrasonic flow meter, vortex flow meter, orifice plate and Coriolis flow meter are discussed in the following sections.

3.3.1 Operating Principles and Accuracy

3.3.1.1 Electromagnetic Flow Meter



Figure 3.17: *Electromagnetic flow meter (Source: Siemens)*

Electromagnetic flow meters operate on Faraday's Law of Electromagnetic Induction to determine the flow of liquid in a pipe.

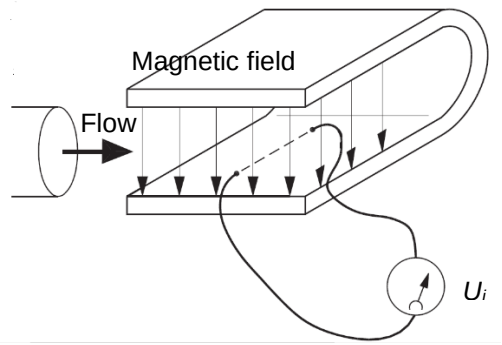


Figure 3.18: *Faraday's Law of electromagnetic induction (Source: Siemens)*

Faraday's Law states that a voltage will be induced when a conductor moves through a magnetic field. It relates that voltage generated is proportional to the movement of the flowing liquid. In this case, the liquid serves as the conductor while the magnetic field is created by energized coils outside the flow tube. The electronic transmitter processes the voltage signal to determine liquid flow. Mathematically, Faraday's Law is stated as

$$U_i = L \times B \times v = k \times v$$

where U_i is the induced voltage and it also represents the electrode signal which is directly proportional to the fluid density. L is the conductor length and is equivalent to inner pipe diameter i.e. k_1, B is the magnetic field strength and is also represented by k_2, v is the velocity of conductor (media) and $k = k_1 \times k_2$.

The coil current module generates a pulsating magnetizing current that drives the coils in the sensor. The current is permanently monitored and corrected. Errors or cable faults are

registered by the self-monitoring circuit. Measuring errors due to cable capacitance are eliminated due to active cable screening.

Digital signal processor converts the analogue flow signal to a digital signal and suppresses electrode noise through a digital filter. Inaccuracies in the transmitter as a result of long-term drift and temperature drift are monitored and continuously compensated for via the self-monitoring circuit.

Installation Method

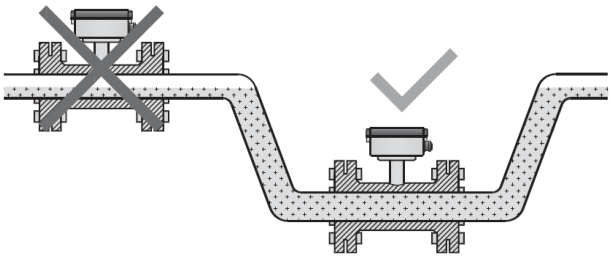
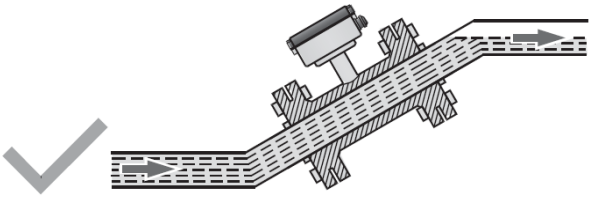
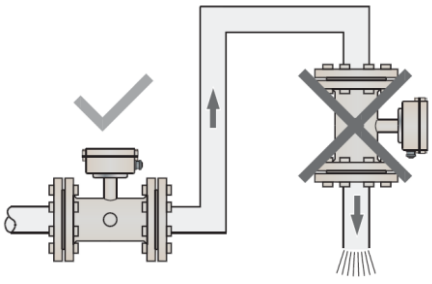
Measurement accuracy of electromagnetic flow meter is also dependent on the proper installation method as per manufacturer guidelines. The following factors shall be considered during installation of an electromagnetic flow meter.

a. Location of flow meter

   The flow sensor must always be completely filled with liquid. Recommended locations for electromagnetic flow meter installation are shown in Table 3-13.

Table 3.13: *Correct location for electromagnetic flow meter installation*

(Source: Siemens)

Recommended Location	Description
	• Locate the flowmeter in u-shaped pipes if pipes are only partially filled or have free outlet
	• Avoid installation at the highest point in the pipe system as the pipes may not be fully filled due to air lock (i.e. gas trapped in a highest point) in the system
	• Avoid Installation in vertical pipes with free outlet i.e. installation shall be at lowest point before any pipe outlet

In order to achieve accurate flow measurement, it is essential to have straight lengths of inlet and outlet pipes and a certain distance to pumps and valves as shown in Figure 3.19. The measurement of straight pipe length shall be taken from the centre of the flowmeter in relation to pipe flanges and gaskets.

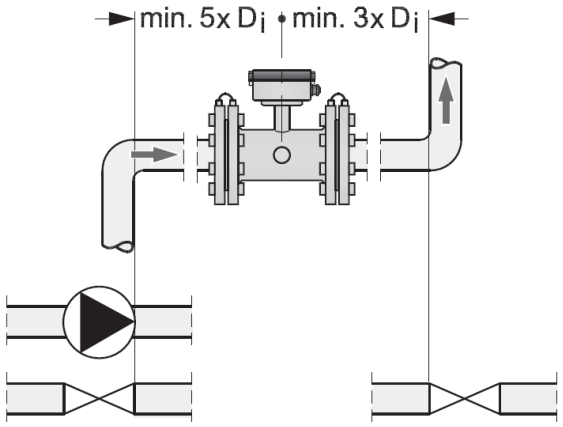
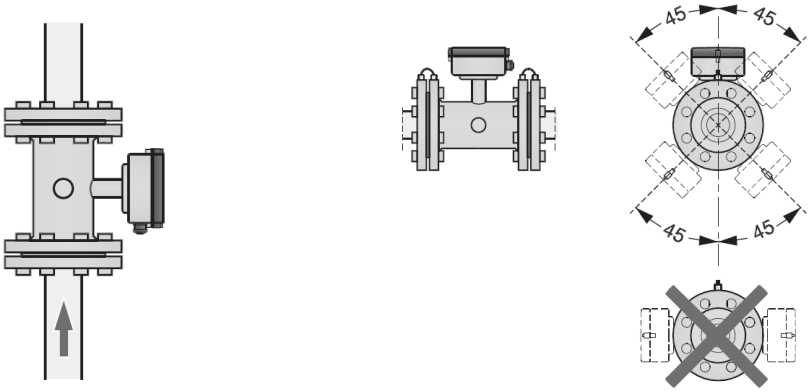


Figure 3.19: *Inlet and outlet conditions with recommended straight pipe length*

(Source: Siemens)

b. Flow sensor orientation

Correct vertical installation with upward flow and horizontal installation are illustrated in Figures 3.20 (a) and (b) respectively.



(a) (b)

Figure 3.20: *Terminal box orientation for (a) vertical upward (b) horizontal installation*

(Source: Siemens)

For horizontal installation, the flow sensor must not be mounted sideways as it will position the electrodes at the top where there is possibility for air bubbles and at the bottom where there is possibility for sludge and sand accumulation.

c. Mounting of flow meter

The flow meter sensor shall be installed in rigid pipelines in order to support the weight of the meter. In order to avoid turbulent flow profiles, the electromagnetic flow meter must be installed centre of connecting pipelines axially. Meanwhile, correctly sized gaskets must be used. The measurement accuracy of flow meter will be affected if the improper gasket is used and if it extends into the flow area.

d. Potential equalisation

To obtain optimum results from the measuring system, the flow sensor must have the same electrical potential as the liquid being measured. This can be achieved by means of built-in grounding electrodes (so called 3rd electrode). The built-in grounding electrode electrically bonds the liquid to the meter to provide a stable and accurate measurement.

Measuring Accuracy

Measurement uncertainties claimed by different electromagnetic flowmeter manufacturers are shown in Table 3.14. Overall, the uncertainty of an electromagnetic flowmeter ranges between 0.2% and 0.5% of flow rate.

Table 3.14: *Comparison of measurement uncertainties of different flow meter models*

Electromagnetic Flow Meter	**Model Type (I)**	**Model Type (II)**
Brand *A*	Maximum error 0.50% of flow rate	Maximum error 0.25% of flow rate
Brand *B*	Standard calibration – 0.4% Class 2	High calibration – 0.2% Class 1

3.3.1.2 Ultrasonic Flow Meter

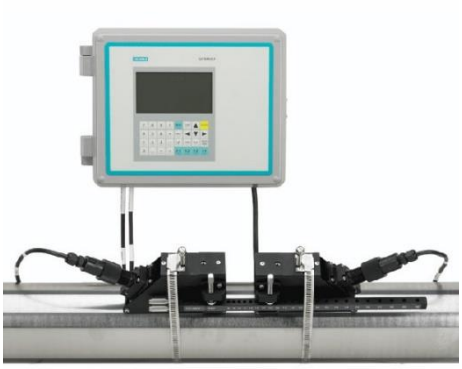


Figure 3.21: *Ultrasonic flow meter*

(Source: Siemens)

Ultrasonic flowmeters can be divided into Doppler meters and time-of-travel (or transit) meters.

The Doppler-shift ultrasonic flow meter, as the name suggests, is based on the Doppler effect. As shown in Figure 3.22, the Doppler-shift ultrasonic flow meter consists of transmit- and receive-node sensors and is mounted in a case attached to one side of the pipe. A signal of known frequency is sent into the liquid to be measured. Solids, bubbles, or any discontinuity in the liquid, cause the pulse to be reflected to the receiver element. The transmit node propagates an ultrasound wave of 0.5 to 10 MHz into the fluid, which is moving at a velocity *v*. It is assumed that the particles or bubbles in the fluid are moving at the same velocity. As this type of ultrasonic flow meter requires sufficient reflecting particles in the fluid, it does not work for extremely pure single-phase fluids.

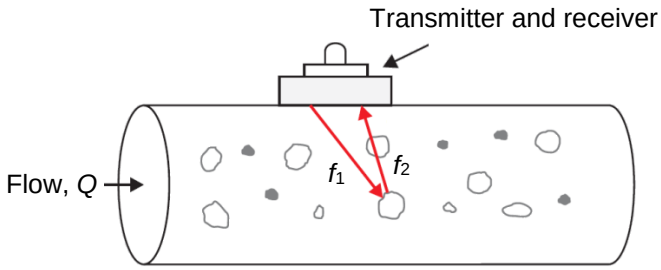


Figure 3.22: *Doppler-shift ultrasonic flow meter (Source: Texas Instruments)*

Figure 3.22 shows the operation principle of Doppler-shift ultrasonic flow meter. The transmitted frequency is varied linearly by being reflected from particles and bubbles in the fluid.

$$v = \frac{\Delta f}{f} \times \frac{C}{\sin\theta}$$

where Δf is the Doppler shift effect and f i.e. f_1, $f_2$is the transmitted frequency, C is the sound velocity and θ is the angle of incidence/reflection. Therefore, the net result is a frequency shift between transmitter and receiver frequencies that is proportional to the velocity of the particles.

On the contrary, the transit-time ultrasonic flow meter can be used for measuring only extremely clean liquids or gases. The liquids being measured must be relatively free of entrained gas or solids to minimise signal scattering and absorption. Transit-time ultrasonic flow meter consists of a pair of ultrasound transducers mounted along an axis aligned at an angle with respect to the fluid flow axis as shown in Figure 3.23.

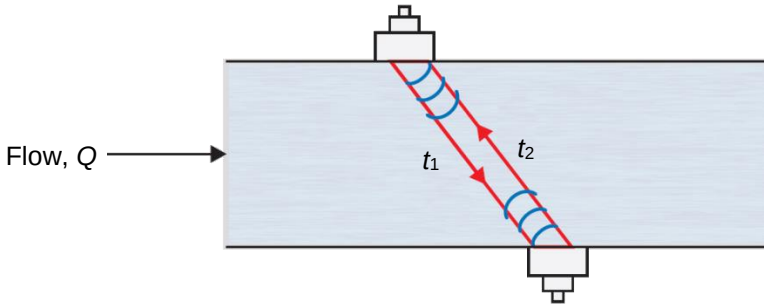


Figure 3.23: *Transit-time ultrasonic flow meter (Source: Texas Instruments)*

These transducers, each consisting of a transmitter/receiver pair, alternately transmit to each other. Fluid flowing through the pipe causes a difference between the transit times of beams traveling upstream and downstream. Measuring this difference in transit time gives flow velocity.

$$Q = K \times (t_1 - t_2) \div (t_1 \times t_2)$$

where Q is the volumetric flow rate, K is a constant that is a function of acoustic path length, ratio between the radial and axial distances from the sensors, velocity distribution (flow-velocity profile), cross section, t_1, t_2 is the transit time for downstream and upstream path respectively.

At no flow conditions, it takes the same time to travel upstream and downstream between the transducers. Under flowing conditions, the upstream wave will travel slower and take more time than the (faster) downstream wave. When the fluid moves faster, the difference between the upstream and downstream times increases. The transmitter processes upstream and downstream times to determine the flow rate.

Installation Method

The ultrasonic flow meter is externally clamped onto existing pipes, allowing installation without cutting or breaking pipes. This avoids disruption to existing system operation and minimises possible system contamination.

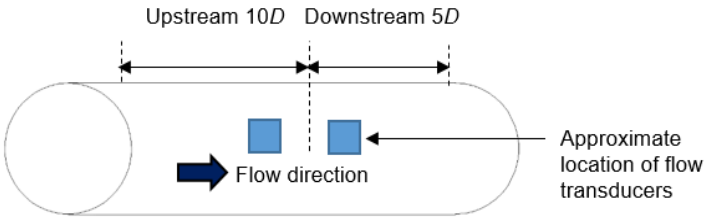


Figure 3.24: *Pipe length requirement for ultrasonic flow meter*

It is recommended that the transducers of ultrasonic flow meters be installed on a straight run of pipe free of valves, flanges or elbows. To measure flow rate accurately, this run of pipe must be at least 15 pipe diameters in length, i.e. at least 10 pipe diameters of straight, undisturbed pipe upstream from the point of measurement and 5 pipe diameters of straight, undisturbed pipe downstream from the point of measurement, as shown in Figure 3.24. However, there are also several ultrasonic flowmeters that do not follow the above guidelines and installation of such flowmeters shall follow specific equipment specifications.

During installation of ultrasonic flow meter, the transducer spacing is calculated in accordance to the manufacturer guidelines. The transducers can be installed on a horizontal run of pipe or a vertical run of pipe with flow going up. However, installation on a vertical run of pipe with flow going down shall be avoided unless it is known that the pipe will always be full.

If the pipe is extremely rough, the ultrasonic signal will be scattered by the rough surface and will not be received by the receiver of the flow meter, preventing flow measurement.

In addition, for horizontal pipe runs, transducers should be placed within a cone 30° above and 30° below the horizontal axis of pipe to avoid signal interference from air and sediment.

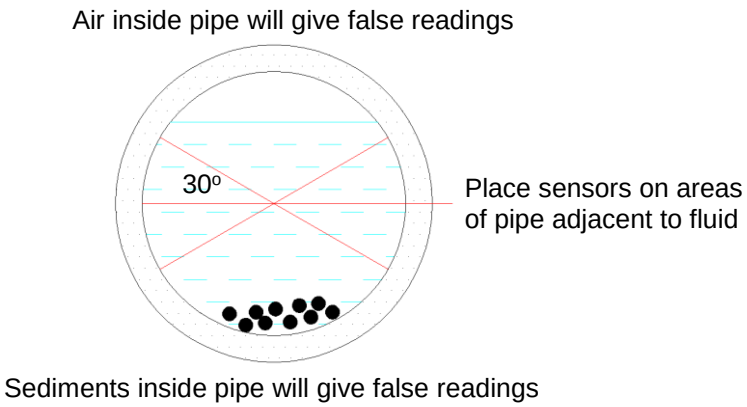


Figure 3.25: *Transducer placement on horizontal pipe run*

Measuring Accuracy

In general, Doppler ultrasonic flow meters are less accurate than transit-time ultrasonic flow meters. However, the cost of the Doppler type is less expensive. The typical measuring uncertainty of Doppler ultrasonic flow meter is within the range of between 1% and 2%. For transit-time ultrasonic flow meter, the typical measuring uncertainty ranges from 0.35% to 2%.

3.3.1.3 Vortex Flow Meter

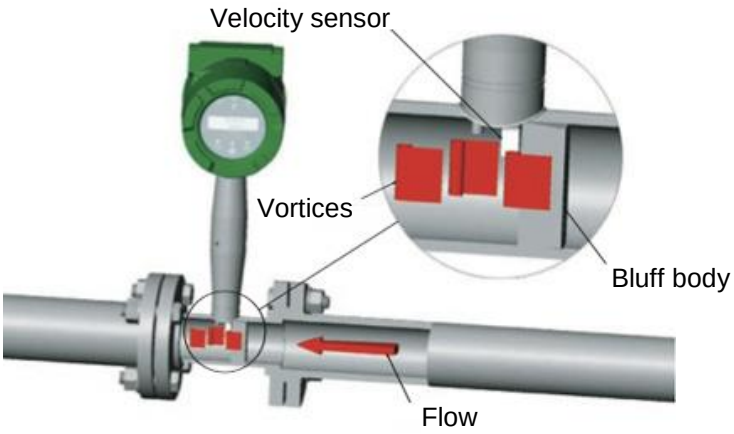


Figure 3.26: *Vortex flow meter*

(Source: Vortek Instruments)

Vortex flow meters measure flows of liquid, gas and steam by detecting the frequency at which vortices are alternatively shed from a bluff body. According to physical laws, the frequency at which the vortices are shed is directly proportional to the flow velocity. As flow passes a bluff body in the flow stream vortex meter, the vortices create low and high pressure zones behind the bluff body, or shedder bar. The pressure exerted by the vortices on the velocity sensor is detected by the flow meter sensor, normally a piezoelectric type.

The sensor then converts these “pulses” into electrical signals which are then converted to a frequency by the meter`s electronics allowing the volumetric flowmeters to calculate the volumetric flow rate to be determined.

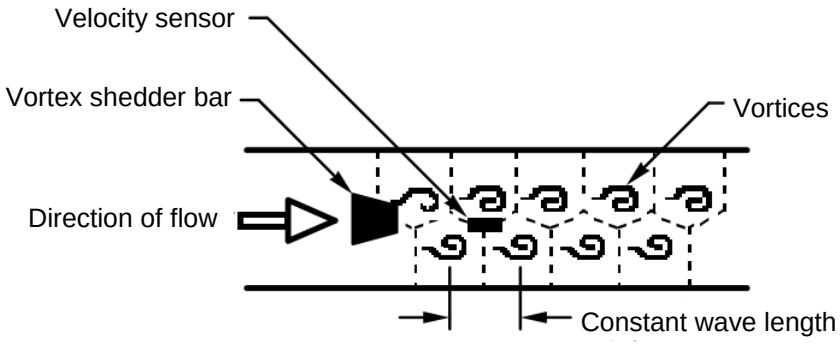


Figure 3.27: *Measuring principle of vortex flow meter*

(Source: Vortek Instruments)

Vortex flowmeters make use of a principle called the von Kármán effect. The Strouhal number is a dimensionless number that quantifies the vortex phenomenon. The Strouhal number is defined as:-

$$S_t = \left(\frac{f\ d}{V_{average}} \right)$$

$$Q = AV_{average} = \frac{f dA}{S_t}$$

where S_t is the Strouhal number, f is the frequency of the shedding, d is the width of the bluff body and $V_{average}$ is the average velocity of the fluid. The volumetric flow rate of the fluid, Q is determined by the above governing equation, where A is the cross-sectional area of the flow meter body.

The accuracy of vortex meters is from medium to high, depending on model and manufacturer. In addition to liquid and gas flow measurement, vortex flowmeters are widely used to measure steam flow. Table 3-15 shows the measurement uncertainties of vortex flow meter of Brand Y.

Table 3.15: *Measurement uncertainties of Brand Y's vortex flow meter*

Process	**In-line type**		**Insertion type**	
Variable	**Liquid**	**Gas & Steam**	**Liquid**	**Gas & Steam**
Volumetric Flow Rate	±0.7% of rate over a 30:1 range	±1.0% of rate over a 30:1 range	±1.2% of rate over a 30:1 range	±1.5% of rate over a 30:1 range

3.3.1.4 Orifice Flow Meter

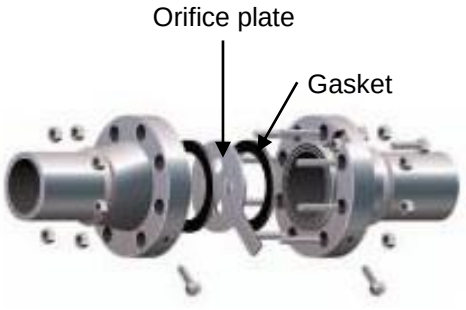


Figure 3.28: *Orifice plates*

An orifice is simply a flat piece of metal with a specific-sized hole bored in it. Most orifices are of the concentric type, but eccentric, conical (quadrant), and segmental designs are also available.

In practice, the orifice plate is installed in the pipe between two flanges. Acting as the primary device, the orifice constricts the flow of liquid to produce a differential pressure across the plate. Pressure taps on either side of the plate are used to detect the difference. Major advantages of orifices are that there are no moving parts and the cost does not increase significantly with pipe size.

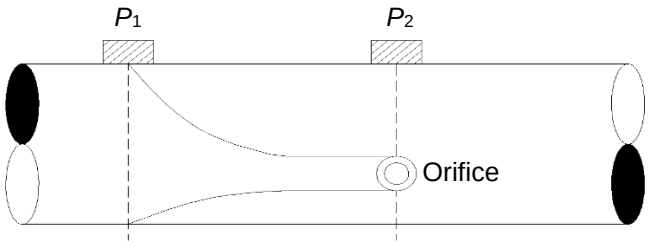


Figure 3.29: *Measuring principle of orifice flow meter*

Orifice flow meter operates based on Bernoulli's principle. It measures the differential pressure across a constriction in the flow's path to infer the flow velocity. As the fluid flows through the hole in the orifice plate as shown in Figure 3.29, in accordance with the law of conservation of mass, the velocity of the fluid that leaves the orifice is higher than the velocity of the fluid as it approaches the orifice.

By Bernoulli's principle, it means that the pressure on the inlet side is higher than the pressure on the outlet side. Measuring this differential pressure gives a direct measure of the flow velocity from which the volumetric flow can easily be calculated.

Measuring Accuracy

Metering accuracy of all orifice flowmeters depends on the installation conditions, the orifice area ratio, and the physical properties of the liquid being measured. If a typical orifice plate is designed and manufactured according to a recognised standard, it is reasonable to expect that the flowrate uncertainty will be approximately 1% or less when the system is flowing at the maximum flowrate under ideal conditions. However, the flow measurement uncertainty could increase by as much as 4% because of installation effects, such as insufficient upstream and downstream straight pipe lengths.

3.3.1.5 Coriolis Flow Meter

Coriolis flow meter directly measures mass flow rate. The installation of Coriolis flow meter can include a single straight tube or a dual curved tube. A popular unit consists of a U-shaped flow tube enclosed in a sensor housing connected to an electronics unit, as shown in Figure 3.30.



Figure 3.30: *Coriolis flow meter (Source: Siemens)*

In a Coriolis flow meter, if there is no fluid flowing through the tubes, they simply vibrate toward and away from each other in parallel and the outputs of the upstream and downstream motion sensors are in phase. While when material flows through the tube, Coriolis effect causes the downstream of the loop to slightly lead the upstream (i.e. the upstream side of the loop to fall slightly behind the downstream side) which creates a slight twist in the loops of tubing as shown in Figure 3-31. This twisting is due to Coriolis acceleration acting in opposite directions on either side of the tubes and the fluid's resistance to the vertical motion.

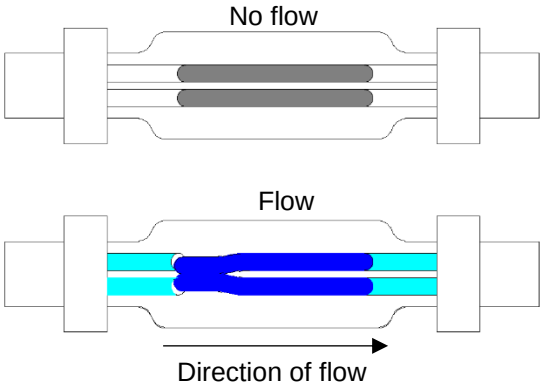


Figure 3.31: *A dual tube in a Coriolis flow meter*

The amount of twist and hence the phase difference between the outputs of the upstream and downstream pick-off sensors, varies linearly with the rate at which mass is flowing through the tubes. Phase is converted to time and time delay is directly proportional to mass flow rate.

This principle applies regardless of whether the fluid is a liquid or gas. Meanwhile, the natural vibration frequency of the tubes is determined by its stiffness and mass and is directly related to the density of the liquid inside the tubes.

Coriolis flow meter sensor can make simultaneous measurements of flow rate and density because the basic oscillating frequency of the tube(s) depends on the density of the fluid flowing inside. However, it cannot measure flow rate of fluids with entrained particles because such particles dampen the tube's oscillations, making it difficult to take accurate measurements.

Measuring Accuracy

Although Coriolis flow meter can cause high pressure drop across the system, this meter has extremely high accuracy. The typical measurement uncertainty of a Coriolis flow meter is ±0.2% of flow rate for liquid and ±0.5% of flow rate for gases.

Table 3.16 shows the comparison between different types of flow meters.

Table 3.16: *Comparison between different types of flow meters*

Feature	Velocity Flow Meter (Magnetic)	Velocity Flow Meter (Ultrasonic)	Differential Pressure Flow Meter (Orifice)	Mass Flow Meter (Coriolis)
Measurement type	Volume	Volume	Volume	Mass
Fluid type/ Flow rate	Not suitable for gas flow	Not suitable for gas flow	Not suitable for gas with low flow rate	Not suitable for very high flow rate (>20,000 l/min)
Particulate flow/ Slurry	Conditionally suitable	Conditionally suitable	Not suitable	Conditionally suitable
Installation/ Maintenance	Moderate installation with minimal maintenance	Easy installation and maintenance	Easy installation; periodic cleaning required	Installation outlay can be considerable; relatively maintenance-free
Typical accuracy	0.2% to 1.0% of reading	1% of reading to 2% of full-scale (Doppler-shift meter)	0.6% to 2% of full scale	0.1% to 0.5% of reading

Feature	Velocity Flow Meter (Magnetic)	Velocity Flow Meter (Ultrasonic)	Differential Pressure Flow Meter (Orifice)	Mass Flow Meter (Coriolis)
		0.35% of reading to 2% of full scale (Transit-time meter)		

3.3.2 Calibration of Flow Meter

All flowmeters require an initial calibration. Most manufacturers calibrate a meter for the specified service conditions. If qualified personnel are available, the user can either perform their own calibrations or hire an external consultant in the laboratory.

The need to recalibrate usually depends on the flow meter application and types of liquids flowing through the flow meters. Over time, portions of the device will deteriorate to affect performance and accuracy. Some flow meter designs are more susceptible to damage than others. Most manufacturers will recalibrate a meter in their plant or in the user's facility.

In general, calibrations of liquid flow meters are performed with primary standards that are based on measurements of the more fundamental quantities i.e. length, mass, time. Primary flow calibrations are accomplished by timed collection of the measured mass of water flowing through the meter under test (MUT) during almost steady conditions of flow, pressure, and temperature. All quantities measured with respect to the calibration standard (i.e., temperature, mass, time, etc.) shall be traceable to established international standards. The flow measured by the primary standard is determined along with the average of the flow indicated by the MUT during the collection at specific interval. It is common that an additional flowmeter is utilized to set the test flows and to monitor the flow stability.

Three fundamental component parts of a water flow calibration facility consists of the followings.

a. Flow generation system
   It consists of storage tank and pumping system. Water flow across the test section is controlled by modulating the control valves. A constant water flow rate is required.
b. Test section
   The piping system of the calibration facility shall be able to implement ideal flow conditions for flow meters. Any disturbance that might affect the MUT shall be avoided..
c. Gravimetric reference system
   This is the part of the calibration system that directs the flowing water into the collection tank while utilizing a clock or timer to determine the collection time. The water collected can be determined in terms of volumetric or gravimetric units.

The above primary flow meter calibration method provides traceability for flowmeter manufacturers, secondary flow calibration laboratories, and flowmeter users.

The primary flow meter calibration test facility is designed to have uncertainty levels that are lower than high-performance flowmeters or secondary standards so that it provides flow traceability, traceability to the international standard for mass, time and temperature.

The uncertainty of each of the input quantities during flow calibration steps is determined, weighted by its sensitivity coefficient, and combined with the other uncertainty components to arrive at the combined uncertainty, using the root-sum-squared technique.

3.4 Air Flow Meter

3.4.1 Operating Principles and Accuracy

The airflow meter measures air velocity and air pressure. Depending on the type of application, the airflow meter is made as a hot-wire airflow meter or a pocket weather flow meter, both of which can measure air velocity and air pressure.

There are several types of airflow meters used in the industry. The common ones are:

a. Pitot tube
b. Pitot array
c. Thermal dispersion duct probe
d. Handheld hotwire anemometer
e. Handheld propeller fan anemometer

A detailed description of operating principles of air flow meters are described in Chapter 5.

3.4.2 Calibration of Air Flow Meter

The choice of calibration method for gas (air) flow meter is governed by the meter type, the ranges of flow and flow conditions, pressure, temperature and the accuracy of calibration required. The main difference between the calibration of a gas flow meter and a liquid device is the compressibility of the fluid. When calibrating a gas flow meter, the temperature, pressure and hence volume of gas measured by the standard will be different from that of the device under test; corrections to common conditions must therefore be made. It is often best to convert to mass flow at the calibrator then back to volume using the conditions of the device under test conditions.

3.4.2.1 Primary Standard Flow Measurement

Primary standard flow measuring devices measure volume based on measured dimensions (i.e. length). Examples of primary standard flow measuring devices are soap film burette, spirometers and sealed piston devices.

Soap film burette is a pipe prover used for both calibration and measurement. A glass tube is vertically mounted with a reservoir of soap dissolved in water below the gas or air inlet. As the gas enters the burette, a soap film is generated and travels up the tube at the same velocity as the gas. By measuring the time of traverse of the soap film between graduations at either end of this accurately calibrated burette, the rate of flow of the gas may be obtained.

What is created is a pipe prover with the displacer formed by the soap film. This method is usually used to measure gas flows within the range 10^{-7} to 10^{-4} m^3/s at close to ambient conditions. Under very carefully controlled conditions, reference flows can be determined to within ±0.25% using soap film burettes.

Another primary standard flow measuring device is spirometers. A cylinder that is opened at the bottom and closed at the top is lowered into a liquid bath. The weight of the cylinder is supported by a wire, string or chain and counter balanced by weights. By altering the counterbalance weight a pressure can be generated in the cylinder. A pipe passing through the liquid is open to the trapped volume and, as the cylinder is lowered, gas is displaced from the cylinder to the meter on test. By timing the fall of the cylinder and knowing the volume and length relationship for the cylinder, the volume flow of gas through the meter may be determined and compared with the meter reading.

In order to minimise expansion or contraction of the gas, gas and external air temperatures should not differ by more than 1°C. Errors can also arise due to incorrect compensation for change in buoyancy of the bell as it is immersed and the gas is not fully saturated. At present, for flows up to some 10^{-2} m^3/s, spirometer can be used to measure flows to within ±0.2% if strict precautions are taken to minimise the errors.

3.4.2.2 Secondary Standard Flow Measurement

Secondary standard flow measurement devices require calibration against primary devices as they may not be as accurate as primary measuring devices. Rotameters, wet test meters and dry gas meters are some examples of secondary flow measuring devices.

A rotameter consists of a float raised by the air flowing up a vertical tapered shaft. The higher the float goes, the larger the area around it becomes and the air flow and float will reach some equilibrium point that represents a certain flow rate. This flow rate value is compared to a primary standard at the manufacturer factory. While these devices may be both accurate and reliable, they are not considered as primary standard flow measuring devices.

A typical apparatus setup for air flow meter calibration consists of the followings.

a. Sampling pump
b. Soap bubble meter (primary)
c. Rotameter (secondary)

All calibration apparatus except soap bubble meters must be corrected for density. The following shall be applied to calibrate each other in the above apparatus setup.

a. Calibration of rotameter using soap bubble meter
b. Calibration of sampling pump using rotameter
c. Evaluation of atmospheric pressure on rotameter performance
d. Calibration of a rotameter with an electronic soap bubble meter

3.5 Pressure Meter



Figure 3.32: *Double-port pressure transmitter*

(Source: ABB)

Different pressure meters can be used to measure various forms of pressure. There are 3 types of pressure measurement i.e. gauge pressure, absolute pressure, and differential pressure which are all related to each other. Both electronic and pneumatic pressure transmitters are deployed to meet the pressure measurement requirement in each application. The following are the pressure measurement applications.

a. Differential pressure

   Differential pressure is the difference in magnitude between a pressure value and a reference pressure.

b. Flow

   A primary flow element creates an internal restriction in fluid piping system. This restriction causes fluid velocity to increase as it passes by the restriction and hence changes in kinetic energy. Either pressure or differential pressure transmitter can be used to measure upstream and downstream pressure.

c. Liquid level

   Liquid level measurements can be made using a differential pressure type transmitter or gauge pressure type transmitter. Typically, this is determined based upon whether the tank is open to the atmosphere or whether it is closed.

d. Density

   In this case, a homogenous liquid of changing density in the tank will exert varying pressure on the transmitter depending on the change in density. Typically, as in level measurement, a differential pressure transmitter is used because the spans are relatively low.

3.5.1 Operating Principles and Accuracy

Configuration

Pressure is measured by means of transmitters that generally consist of two main parts.

a. Sensing element, which is in direct or indirect contact with the process; and
b. Secondary electronic package which translates and conditions the output of the sensing element into a standard transmission signal.

The primary sensing element is connected to the piping in such a way that the piping pressure is exerted against the isolation diaphragm(s). According to Pascal's Law, the fill fluid inside the primary element will reach the same pressure as that applied against the isolation diaphragm(s). The fill fluid hydraulically conveys this pressure to the sensor, which in turn produces an appropriate output signal.

The secondary electronics of the transmitter filter, amplify, condition, and convert the sensor signal into a standard 4-20 mA DC output signal. The output of the sensor is compensated for variations in process and ambient conditions before being converted to a 4-20mA signal. This minimises unwanted measurement errors due to temperature effects.

Measuring Principles

Pressure meter utilises Pascal's Law as its basic principle in employing the pressure sensing element. Pascal's Law states that whenever an external pressure is applied to any confined fluid at rest, the pressure is increased at every point in the fluid by the amount of that external pressure.

The most common effective sensing methods used in pressure meters as per today's technology are listed as follows.

a. Electromechanical strain gauge

   This type of sensors convert pressure into relatively small resistivity changes. The change in resistance typically affects the four legs of a Wheatstone bridge circuit as shown in Figure 3.33. Strain gauge sensors located in the primary sensor usually take the place of two of the resistor legs in an energized Wheatstone bridge circuit. When a pressure is applied to the transmitter, the resistance of the strain gauges changes, unbalancing the bridge and creating a proportional differential voltage across the test points. The transmitter electronics converts this voltage signal into a 4-20 mA signal for transmission.

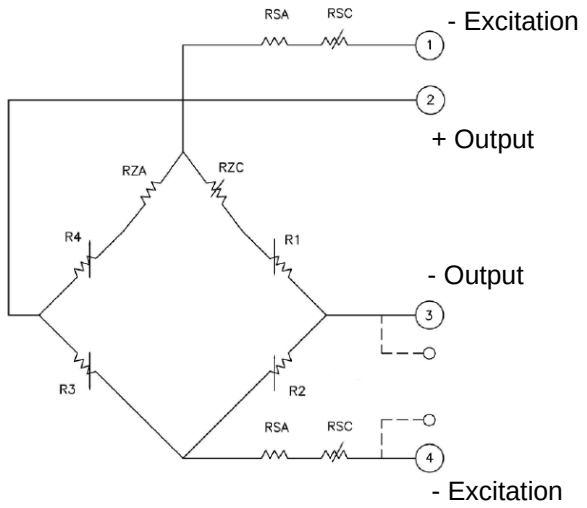


Figure 3.33: *Wheatstone bridge circuit*

(Source: ABB)

b. Variable capacitance

For variable capacitance sensor, an increase in pressure on the diaphragm is transmitted through the fill fluid to the ceramic diaphragm in the capacitance sensor. The pressure increase causes the diaphragm to bulge, thus changing the distance between the diaphragm and the reference plate.

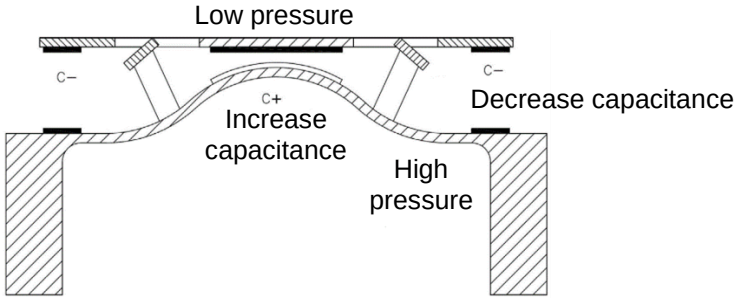


Figure 3.34: *Variable capacitance sensor operation*

(Source: ABB)

This change in distance is very small. The change in the ratio of the decrease capacitance and increase capacitance feeds the logic circuit of the transmitter. The output current regulator produces an increase in transmitter output current, which is proportional to the increase in process pressure.

c. Variable reluctance

Variable reluctance elements are being employed to detect small displacements of capsules or other sensors for direct coupling between pressure sensitive elements and amplifier circuits.

For variable reluctance pressure sensor, the inductance in a pair of coils is affected by changes in the magnetic coupling of the diaphragm, which is mounted between the two coils. With applied pressure, the sensing diaphragm will deflect towards one coil and away from the other. The position of the sensing diaphragm enhances the magnetic flux density of the closest coil, while decreasing the flux density of the furthest coil. Increasing the magnetic flux density of a coil will increase the induction and impedance of the coil.

d. Piezo-resistive

Piezo-resistive sensors can be considered as the semiconductor technology version of the electromechanical strain gauge that is described above.

The Piezo-resistive sensor consists of a semiconductor element that has been doped to obtain a piezo-resistive effect. Its conductivity is influenced by a change that can be produced by an extremely small mechanical deformation.

Measuring Uncertainty

Depending on the pressure measurement application requirements, the measuring uncertainty of a pressure meter ranges from 0.025% to 0.50%. This depends on the application requirements.

3.5.2 Calibration of Pressure Meter

The most important consideration in selecting a reference instrument is traceability. In pressure terms, traceability is defined as the ability to trace the calibration of a given measurement either directly or indirectly to standards of mass and length.
A primary pressure standard is a pressure measuring instrument, which can reduce pressure measurements into measurements of mass, length and temperature and gravity. For example, pressure balances or dead weight testers and primary mercury barometers. A secondary standard is an instrument which must be calibrated to relate the output directly to pressure. Both standards have advantages and disadvantages.

3.5.2.1 Primary Pressure Standards

The basic principle of the pressure balance consists of a vertical piston freely rotating within a cylinder. The two elements (i.e. measuring element and movable element) of well-machined quality define a surface called the 'effective area'. The pressure to be measured is applied to the base of the piston, creating an upward vertical force. This force is equilibrated by the gravitational downward force due to masses submitted to the local gravity and placed on the top of the piston. The piston itself is also as a part of the load.

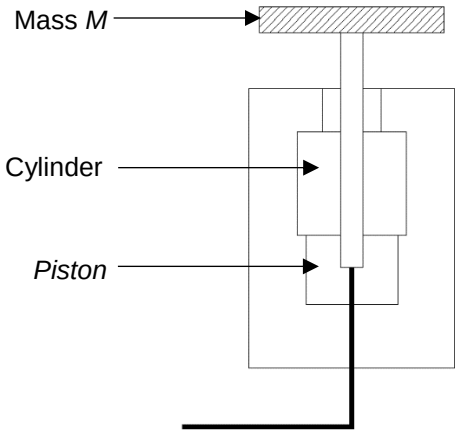


Figure 3.35: *Example of primary pressure standard*

The primary mercury barometer must operate in high vacuum above mercury column, contain highly pure mercury at constant temperature and be located in a pollution safe environment. Figure 3.35 shows an example of primary pressure standard.

The applied pressure can be calculated according to the equation below.

$$p = (1 - L \cdot p) \cdot k_n \cdot \frac{g_1}{g_n} \cdot \frac{N}{N_k} \cdot \frac{p_m - p_a}{p_m - 1.2}\left[1 - \left(\alpha_p + \alpha_c\right) \cdot (t - 20)\right] + \mu + \rho_a \cdot g_l \cdot h$$

Parameter	Description	Value
L	Pressure distortion coefficient of the piston cylinder assembly	< 0.000 Pa^{-1}
p	Pressure measured	[Pa]
k_n	Conversion coefficient of the piston cylinder given in the calibration certificate.	20.00270 kPa- kg^{-1}
g_l	Local gravity – measured	9.80615880 ms^{-2}
g_n	Normal gravity	9.80665 ms^{-2}
N	Readout on the dynamometer DPG	[dig]
N_k	Nominal coefficient of the dynamometer	100000 dig/kg
ρ_m	Mass density – stainless steel AISI 304 L	7920 kg-m^{-3}
ρ_a	Air density during calibration of the dynamometer	[kg-m^{-3}]
α_p	Thermal expansion coefficient of the piston	0.45 x 10^{-5} °C^{-1}
α_c	Thermal expansion coefficient of the cylinder	0.45 x 10^{-5} °C^{-1}
t	Temperature of the piston cylinder assembly	[°C^{-1}]
μ	Residual pressure	[Pa]

Table 3.17 outlines advantages and disadvantages of primary pressure standard.

Table 3.17: *Advantage and disadvantage of primary pressure standard*

Advantage	Disadvantage
Pressure balances are traceable to measurements of mass and length and is more directly to the national standards.	Measurements must be corrected for temperature, local gravity and air buoyancy which can increase probability for error as the corrections are applied.
Good long term stability.	Time consuming operation for day-to-day routine work.
High accuracy, high reproducibility, reliable and stable instrument.	Mercury barometers potentially represent a health and environmental hazard.

3.5.2.2 Secondary Pressure Standards

Secondary pressure standards may be secondary electronic barometers with good long term stability. With recent development of high quality electronic barometers, measuring uncertainty was reduced to few Pascals level. Table 3.18 outlines advantages and disadvantages of secondary pressure standard.

Table 3.18: *Advantages and disadvantages of secondary pressure standard*

Advantage	Disadvantage
Faster and easier to use	Pressure measurements cannot be reduced to measurements of mass, length or temperature
Easy to adapt to automatic operation	Higher measurement uncertainty
Generally less expensive	

Primary and secondary standard calibration devices are typically used and maintained by the calibration laboratory within an organisation. With primary or secondary pressure standards, the laboratory can then either directly calibrate working standards, calibrate travelling standards or calibrate field measuring instruments.

3.6 Lux Meter

3.6.1 Operating Principles and Accuracy

Lux meters are used for measuring brightness in lux, fc or cd/m². Some lux meters are equipped with internal memory or a data logger to record the measurements. It is highly regarded especially due to their cosine correction of the angle of incident light.

The lux is a unit of measurement of brightness, or more accurately, illuminance. It ultimately derives from the candela, the standard unit of measurement for the power of light. A candela is a fixed amount, roughly equivalent to the brightness of one candle. The lumen is a standardised unit of measurement of the total amount of light that is produced by a light source. One Lux is defined as being equivalent to one lumen spread over an area of one square metre.

A lux meter works by using a photo cell to capture light. The meter then converts this light to an electrical current, and measuring this current allows the device to calculate the lux value of the light it captured.

For measurement less than 10,000 lux, the measuring uncertainty of lux meter is ±5% of reading. While for measurement above 10,000 lux, the measuring uncertainty of lux meter is ±10% of reading.

3.6.2 Calibration of Lux Meter

To calibrate a lux meter, a standard calibration-certified lamp with a known luminous intensity is placed opposite a meter that has been oriented for uniform illumination on the sensor. Measurements are taken at five different distances to determine a reference illumination, and the average of these measurements is summed with the correction factor of the reference lamp and the correction factor of the meter's resolution. This value is aligned with the meter's scale.

Most industrial lux meters do not provide an absolute readout—instead they provide a representative value in respect to their tolerance and resolution. Laboratory-calibrated lux meters are available for such applications, but will eventually need to be recalibrated. Some manufacturers recommend removing the photodetector cover several minutes before measuring a sample to reduce potential adaptation sensitivity in the sensor.

4 Measurement and Analysis of Chilled Water System

Introduction

For air-conditioned buildings in tropical region, up to 50% or more of the total electricity consumption consists of the operation of chilled water system. It is important to conduct proper measurement and analysis of chilled water system to uncover operational and chilled water system equipment improvements that will save energy, reduce operating cost and hence lead to more efficient chilled water system performance. The objective of measurement and analysis of a chilled water system is to qualify a measurement system, by deploying proper and high accuracy instrumentation.

Singapore Standard SS 591:2013 Code of Practice for Long Term Measurement of Central Chilled Water System Energy Efficiency specifies the requirements for sensors and instruments in capturing relevant process parameters, their installation, commissioning, operational monitoring and maintenance in order to perform continuous, long term measurement of central chilled water system energy efficiency. The standard specifies required uncertainty limits, parameters and performance indicators for continuous measurements of equipment and chilled water system energy efficiency. It also recommends the development of useful presentation formats for the data collected, to be used widely and on various platforms, including web-based platforms.

Learning Outcomes

Participants will be able to:

i. Acquire Level I and Level II skills in chilled water system measurement and analysis.
ii. Appreciate the depth of Level III chilled water system measurement and analysis and be able to assess the outcome of Level III chilled water system audits.

4.1 Level I to Level III Scope of Work

There are three levels of energy audits

4.1.1 Level I Assessment – Preliminary or Walk-through

A level I assessment, sometimes also referred to as a preliminary assessment, evaluates the overall energy consumption of the facility and is expected to provide a rough estimate of energy savings, investment costs and payback of the preliminary recommendations.
This assessment is usually designed to determine if the level of energy use of a facility has been reasonable or excessive. It provides initial energy baselines of the facility so that the effect of energy measures may be evaluated. It may or may not involve a site visit. The information given to or gathered by the ESCO needs to be sufficient to enable the overall efficiency of the facility to be ascertained.

The scope of work for level I appraisal is as follows:

- Gather facility-wide energy use on a monthly and/or annual basis;
- Derive performance indicators;
- Propose broad conclusions and recommendations, with estimated energy savings and payback; and
- Submit written report.

4.1.2 Level II Assessment – Standard

A level II assessment identifies the actual amount of energy used by a facility the source of the energy and what the energy is used for. It also identifies areas where savings may be achieved, recommends measures to be taken and provides a statement of expected costs and potential savings. It also involves short term metering and logging.

The expected scope of work for level II assessment is as follows:

- Follow-up from level I assessment and report where available;
- Facility investigation;
- Detailed facility and systems energy input and energy use;
- Reconciliation of energy accounts with loads;
- Variation on energy use on a month-to-month basis;
- Energy performance indicators;
- Recommended improvement work with indicative costs and savings;
- Implementation priority and plan;
- Alignment of recommendations with client's energy program; and
- Written report and presentation.

4.1.3 Level III Assessment – Comprehensive or Detailed

Level III assessment is similar to a level II assessment except it also involves long-term detailed metering and data logging. A level III assessment provides a detailed analysis of energy usage, the savings that can be made and the cost of achieving those savings. It may cover the whole facility or may concentrate on an individual item and/or system, such as a single industrial process or one of the services.

The expected scope of work for level III assessment is as follows:

- Follow-up from level II assessment and report where available;
- Define facility/process audited;
- Facility/process investigation and detailed measurements;
- Detailed metering down to half-hourly time interval where required;
- Derive target energy use and develop baseline model where relevant;
- Detailed recommendations including costs, savings and accuracy of estimates;
- Detailed investment plan;
- Suggest refinement to energy policy and energy program; and
- Written report and presentation.

4.1.4 Checklist for Assessment of Chilled Water System

Chiller

- What is the refrigerant type?
- What is the age of the chiller?
- What is the chiller design efficiency? (i.e. kW/RT at new condition)
- Reliability of the existing chiller?
- Are more chillers operating than necessary?
- High condenser water supply/ return temperature?
- High condenser saturated temperature and/or approach temperature?
- Low evaporator saturated temperature or high approach temperature?

Pump

- What is the age of the pump?
- What is pump design efficiency?
- What is pump motor efficiency?
- What is the pump head?
- Are there secondary pumps?
- What is the pump rated motor power?
- What is the chilled water and condenser water differential temperature?
- Are there any balancing valves?
- Are there throttling of valves?
- Are there high pressure loss fittings?
- Is there any unnecessary by-pass of water?
- Are the pump sets operated with variable speed drive (VSD) and what is the pump operating speed?
- What is the control logic and set point?
- Are there poor pump inlet and outlet connections?
- Are there abnormal noise and vibration? Is shaft seal leaking?

Cooling Tower

The performance of cooling tower depends on the efficient operation of its components.

- Layout arrangement
- Capacity control
- In-fill
- Fan and motor

- Fan belting system
- Water distribution system
- Water level control and float assembly

The above information can be obtained from the chilled water system equipment nameplates or datasheet and data collected from Building Automation System (BAS). Alternatively, an interview session could be done with the technical/ facility engineer.

4.2 Types of Instruments and Accuracy

In Chapter 3, measuring accuracies of different measurement instruments were discussed in detail. Table 4.1 summarises the types of instruments and their accuracies.

BCA Green Mark for New Non-Residential Buildings (Version 4onwards) and Existing Non-Residential Buildings (Version 3 onwards) require buildings to provide accurate permanent measurement and verification instruments to monitor the operating system efficiencies of water-cooled and air-cooled chilled-water systems. The installed instrumentation shall have the capability to calculate resultant plant operating system efficiency (i.e. kW/RT) within 5% of its true value and in accordance with ASHRAE Guide 22 and AHRI 550/590. Each measurement system shall include the sensor, any signal conditioning, the data acquisition system and wiring connecting them. Heat balance test for water-cooled chilled water system is required for verification of the accuracy of the M&V instrumentation. The heat balance shall be computed over the entire building's normal operating hours, over a one-week period, with more than 80% of the computed heat balance to be within ±5%. Please refer to section-1.3.4 for the building's normal operating hours.

Measurement and verification can also be used as an accountability tool to determine the performance of the supplied equipment post installation. SS591:2013 specifies that the overall measurement system shall consist of temperature, flow and power measurement systems. Each measurement system shall include the sensor, any signal conditioning, the data acquisition system and the wiring connecting them. The standard also requires that the instruments used in the monitoring and measurement of the central chilled water system shall be calibrated against measurement standards that are traceable to the national standards or equivalent.

Singapore's approach towards improving and sustaining commercial building energy performance through the use of highly accurate instruments and focus on verifiable results has been published in the ASHRAE Journal, November 2016. For more information about the ASHRAE Journal, please visit www.ashrae.org.

Table 4.1: Measuring accuracy of different types of instruments in the chilled water system

Measurement Parameter	Point Description	Type of Instruments	Instrument Measurement Accuracy
Power	• Main incoming power to chilled water system • Chiller power • Chilled water pump (CHWP) power • Condenser water pump (CDWP) power • Cooling tower power	• Current transducer • Power meter	Class 0.5 Class 1.0 ±1.0% of reading
Temperature	• Chilled water supply (CHWS) header temperature • Chilled water return (CHWR) header temperature • Condenser water supply (CDWS) temperature • Condenser water return (CDWR) temperature • Chiller CHWS temperature • Chiller CHWR temperature • Chiller CDWS temperature • Chiller CDWR temperature • Ambient dry bulb temperature	• Thermocouple • Resistance Temperature Detector (RTD) • NTC Thermistor	0.5 – 5.0°C 0.1 – 1.0°C 0.05 – 1.5°C
Flow rate	• Chilled water header flow rate • Condenser water header flow rate	• Electromagnetic • Ultrasonic	0.2% - 1.0% 1% of reading to 2% of full-scale

Measurement Parameter	Point Description	Type of Instruments	Instrument Measurement Accuracy
	• Chiller chilled water flow rate • Chiller condenser water flow rate		

4.3 Data Collection

The measurement data can fluctuate subjected to the installed conditions and type of instruments deployed. For data display, analysis and recording purposes, all data should be continuously trended over entire chilled water system operating period. The following sections describe useful metrics, types of data to be collected and duration and frequency of data collection.

4.3.1 Useful Metrics

The ultimate goal of measurement and analysis of chilled water system is to monitor and identify the operating performance of chilled water system. Several useful metrics as outlined in ASHRAE Guidelines 22-2012 are listed as follows. These metrics shall be benchmarked against codes and standards (Section 4.5) in order to define the range of expected performance for each metric.

a.) Chiller average efficiency (in terms of kW/RT) is defined as the ratio of the cumulative electrical energy consumption in kWh by the chiller to the cumulative cooling effect in RTh generated by the chiller. Accuracy better than ±2.6% for kW/RT is expected. This performance metric requires cumulative electrical energy consumption of chiller (kWh) and chilled water cumulative cooling output from the chiller (RTh).

b.) Chilled water system average efficiency (in terms of kW/RT) defined as the ratio of the cumulative electrical energy consumption in kWh by the chilled water system (which includes chillers, chilled-water pumps, condenser water pumps and cooling towers) to the cumulative cooling effect in RTh generated by the chilled water system. In accordance to BCA Green Mark Guidelines for New and Existing Non-residential buildings, the objective is to achieve the accuracy of the chilled water system efficiency within ±5%. This performance metric requires the following data points.

- Chilled water system equipment power (kW)
  Instantaneous and cumulative values of the total electrical energy (kWh) consumed by the central chilled water system and the electrical energy consumed (kWh) by each group of equipment such as chillers, chilled water pumps, condenser water pumps and cooling towers.
- Instantaneous and cumulative values of the total cooling load for the chilled water system.

c.) Total cooling load of chilled water system. Instantaneous data to be provided during entire chilled water system operating hours. These data can be translated into load distribution analysis in terms of statistical calculation i.e. frequency plot. The maximum

and average of total cooling load of chilled water system and total cooling load of highest occurrence can therefore be determined.

d.) Chilled water system ambient conditions i.e. outside ambient air dry bulb temperature and relative humidity.

4.3.2 Types of Data to be Collected

In energy assessment of chilled water system, the following types of measured data examples are to be collected for further analysis.

Power

- Individual chilled water system equipment power i.e. chillers, chilled water pumps, condenser water pumps and cooling tower fan motors
- Main total incoming power to chilled water system

Temperature

- Chiller chilled water supply temperature
- Chiller chilled water return temperature
- Chiller condenser water supply temperature
- Chiller condenser water return temperature
- Main and sub-branch of chilled water supply/ return header temperature
- Main condenser water supply/ return header temperature
- Chiller evaporator/ condenser approach temperature (chiller internal sensor)
- Chiller evaporator/ condenser refrigerant saturation temperature (chiller internal sensor)
- Chilled water system ambient dry bulb temperature

Flow rate

- Chiller chilled water flow rate
- Chiller condenser water flow rate
- Main and sub-branch of chilled water header flow rate
- Main condenser header flow rate

Calculated data

- Chilled water system individual equipment efficiency i.e. chillers, chilled water pumps, condenser water pumps and cooling towers

- Chilled water system efficiency
- Total chilled water system cooling load

4.3.3 Duration and Frequency of Data Collection

All measured data of chilled water system are to be logged at 1 minute sampling time interval and recorded to the 3rd decimal digit. The measured data must be trended over the entire chilled water system operating period for a minimum of 1 week. For example, the building operating hours for retail mall could be from 10 a.m. to 10 p.m.; while for hotel the operating hours is 24 hours. Nevertheless, instead of trended data, spot measurement data can also be taken during preliminary assessment of chilled water system. For example, spot measurement of power input to the chilled water system individual components and differential pressure across pumps.

4.4 Data Analysis

4.4.1 Data Arrangements

Collected measured data can be arranged in table format i.e. to include the following information.

- Date
- Time
- Chiller operating data i.e. temperatures, flow rates and power usage
- Pumps operating data i.e. power usage
- Cooling tower operating data i.e. power usage
- Main chilled water header flow rates, temperatures and differential pressure
- Condenser water header flow rates and temperatures

4.4.2 Graphical Representation

Figure 4.1 shows a typical graphical representation of chilled water system on Building Automation System (BAS).

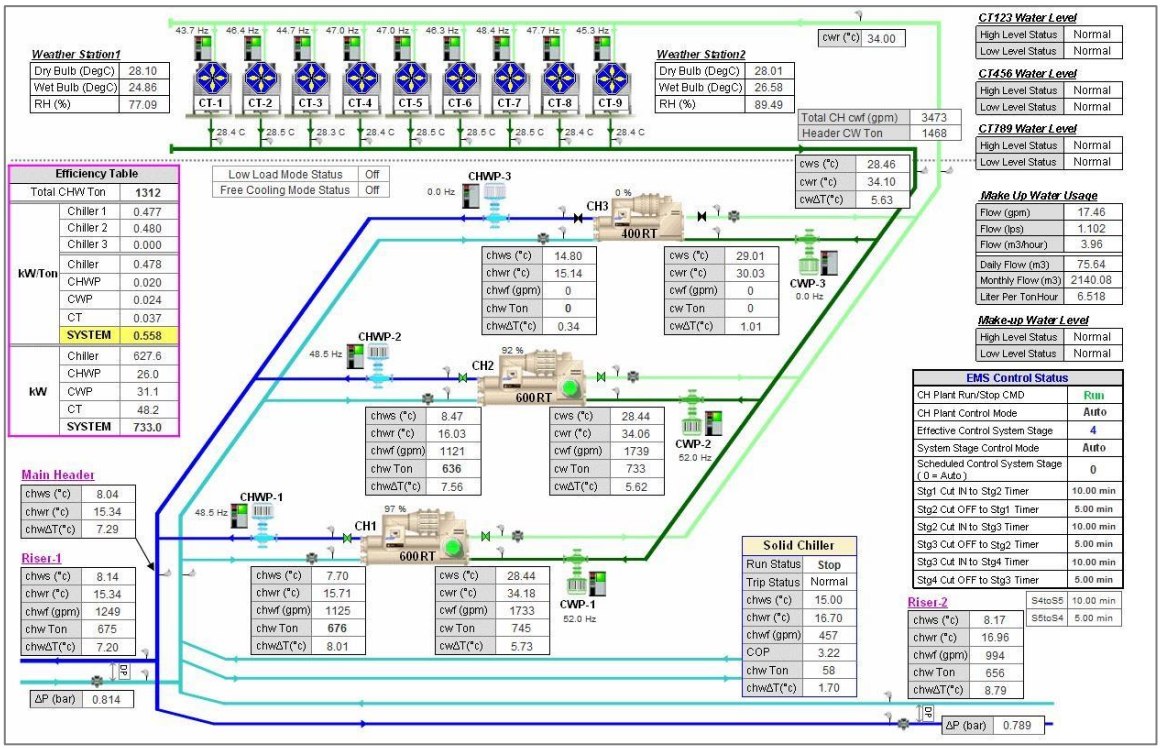


Figure 4.1: *Typical graphical representative of chilled water system on BAS*

The main graphic page displays the following chilled water system information.

- Individual chiller operating parameters such as chilled water temperatures, condenser water temperatures, chilled water flow rate, condenser water flow rate and cooling load
- Main chilled water header operating parameters such as temperatures, flow rate and differential pressure
- Condenser water header operating parameters such as temperature and flow rate
- Chilled water system ambient weather conditions (displayed as weather station)
- Chilled water system efficiency summary table

Clicking onto the main graphic page diverts user to detailed measured data of individual chilled water system equipment. Figure 4.2 illustrates a typical cooling tower detailed graphic page on BAS. It displays cooling tower control approach and variable speed drive operating parameters for cooling tower fans.

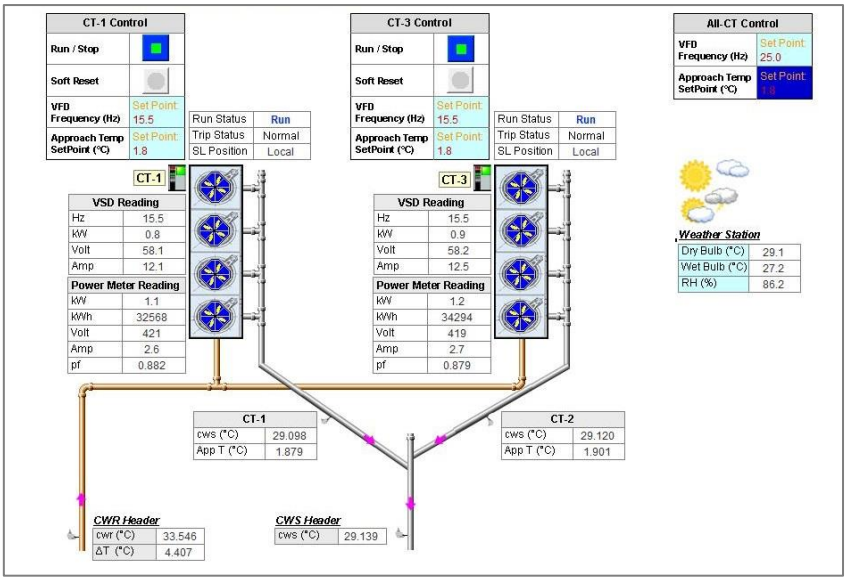


Figure 4.2: *Typical cooling tower detailed graphic page on BAS*

The followings are the basic analysis of chilled water system operating data.

- Chilled water system operating tonnage (time series, frequency plots)
- Chilled water system performance
- Chilled water system equipment power consumed
- Chiller operating parameters e.g. chilled water temperature and flow rate, condenser water temperature and flow rate
- Temperature and flow rate at header levels
- Heat balance analysis

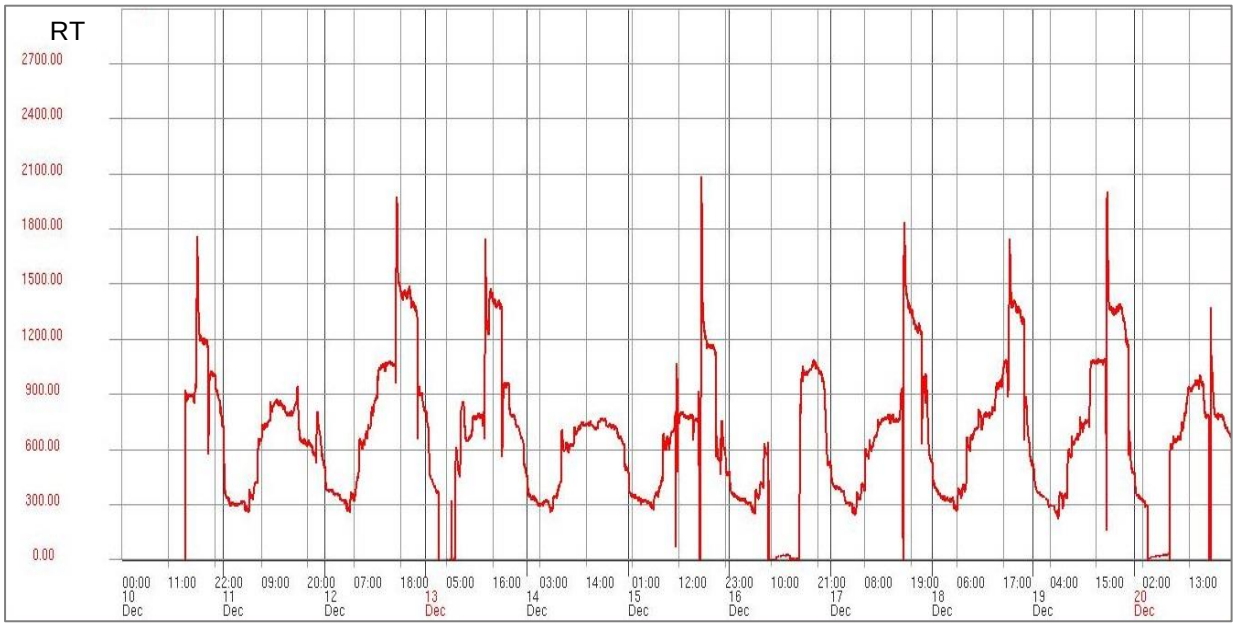


Figure 4.3: *Example of chilled water system cooling load profile in time series*

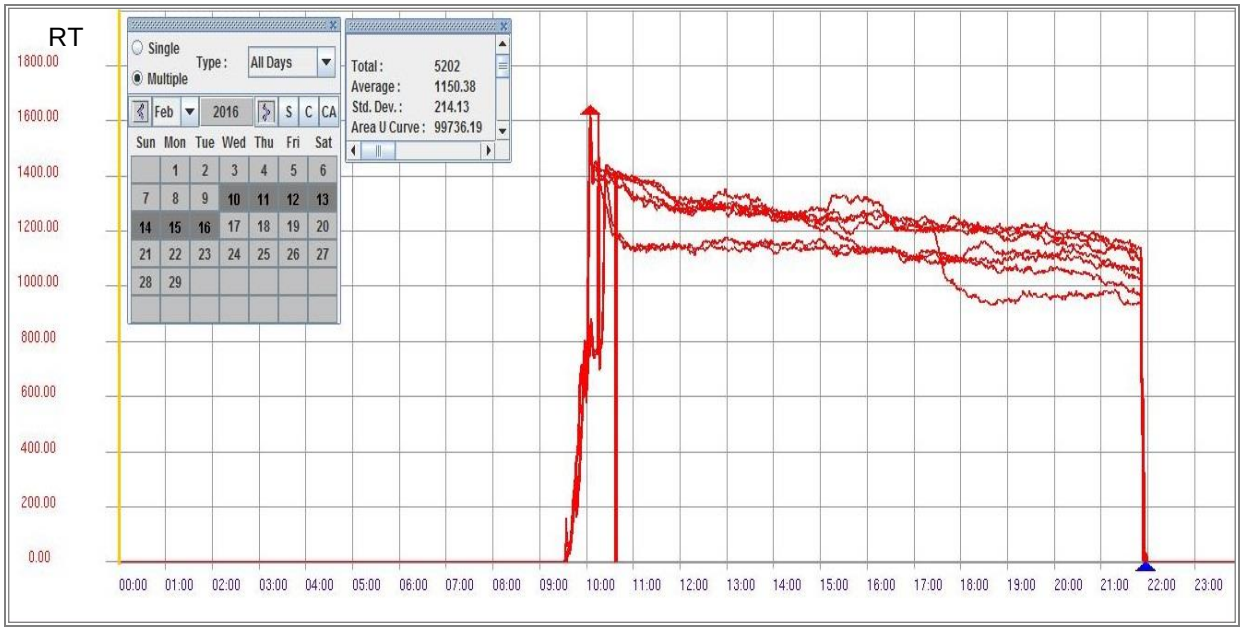


Figure 4.4: *Super-imposed plot of daily chilled water system cooling load*

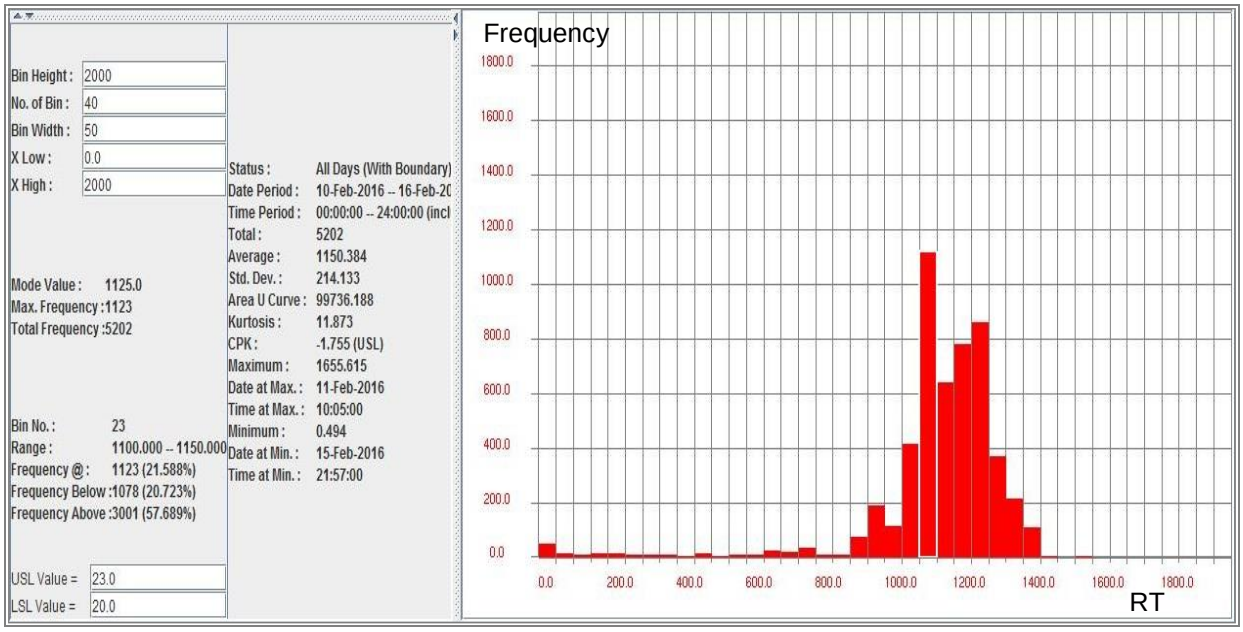


Figure 4.5: *Histogram of cooling load occurrence*

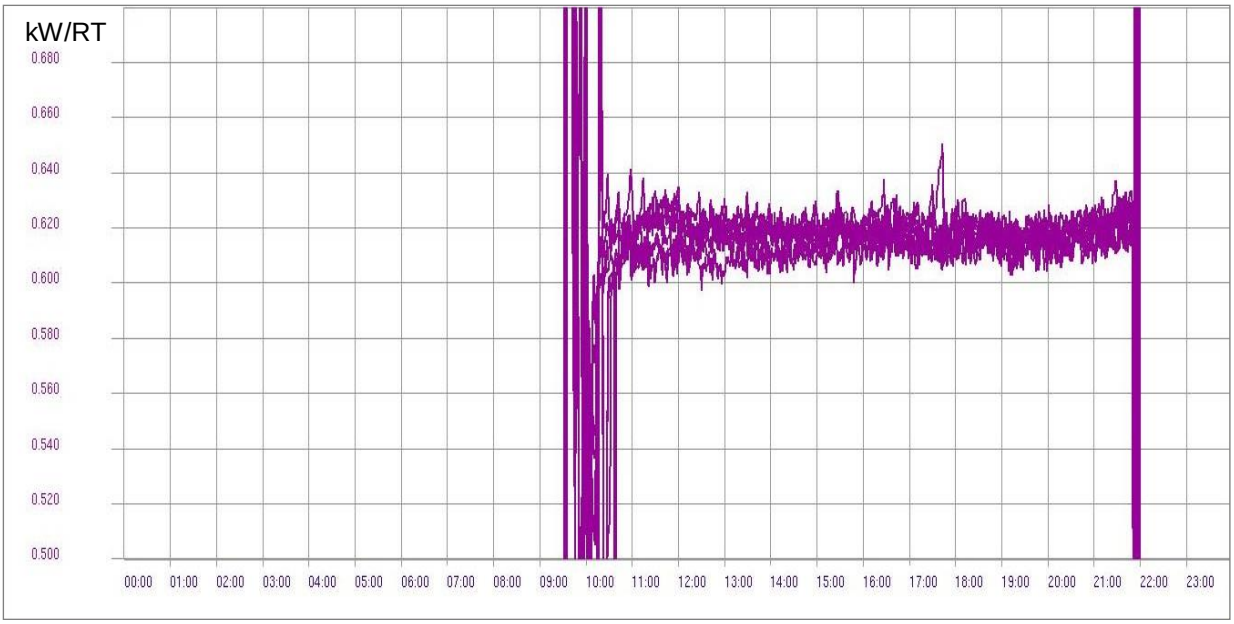


Figure 4.6: *Super-imposed daily plot of chilled water system efficiency*

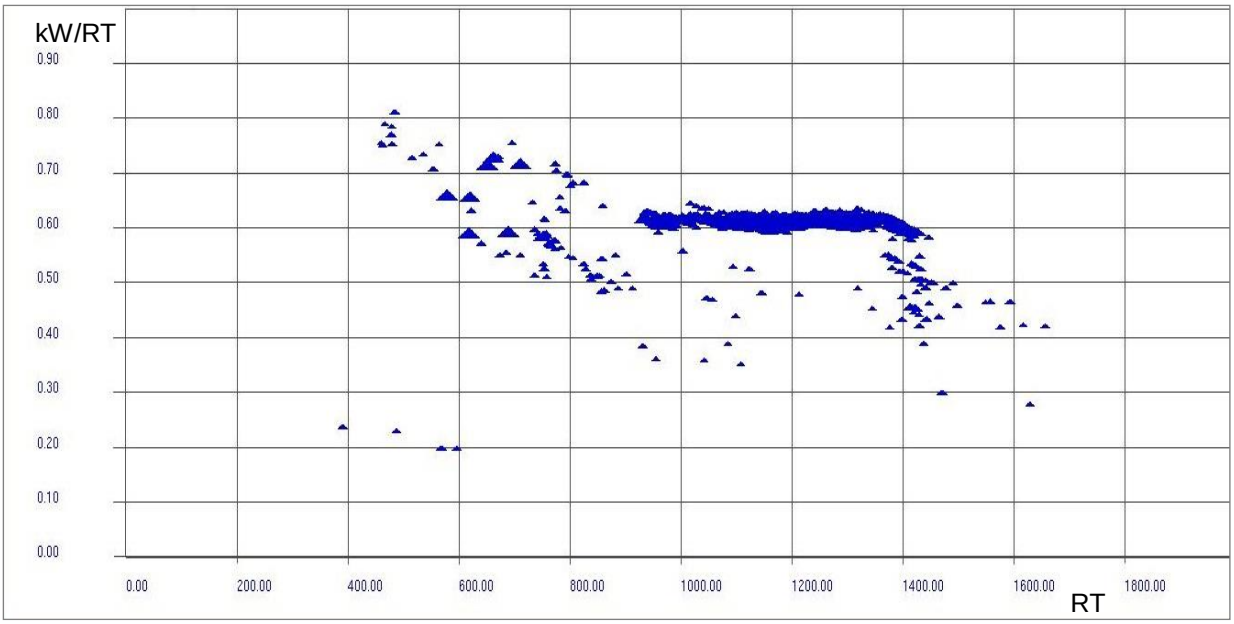


Figure 4.7: *Scatter plot of chilled water system efficiency versus cooling load*

4.4.3 Heat Balance Validation

For large chiller plant systems, on top of a heat balance test for chilled water system, it is good practice to install additional temperature sensors and flow meters at individual chillers as recommended in SS591:2013. The additional sensors can be used to cross check the accuracy of the sensors and it can be used for troubleshooting if the performance of the chiller plant deteriorates.

Additional benefits for the installation of sensors at individual chillers:

a. Installation of flow meters for each chiller will allow control of individual CHWP and CDWP flow rate.
b. Installation of flow meters for each chiller will allow measurement of kW/RT for individual chiller, CHWP, CDWP and CT.

The heat balance can be computed using the following equation:

$$Heat\ balance = \frac{Sum\ of\ heat\ in - Sum\ of\ heat\ out}{Sum\ of\ heat\ out}$$

Under BCA Green Mark for New Non-Residential Buildings (Version 4 onwards) and Existing Non-Residential Buildings (Version 3 onwards), heat balance shall be computed over the entire building's normal operating hours, over a one-week period, with more than 80% of the computed heat balance to be within ±5%. Table 4.2 shows an example of a heat balance summary at system level.

Table 4.2: Example of heat balance error analysis at system level

Description	Unit	Chiller #
Sum of total electrical energy used	kWh	61,431
Sum of total cooling produced	RTh	99,738
Sum of total heat rejected	RTh	117,415
Efficiency of chilled water system	kW/RT	0.616
Total Heat Balance Data Count	-	10,079
Data Count > + 5% error	-	60
Data Count < - 5% error	-	178
Data Count within ±5% error	-	9,841
% Heat Balance within ±5% error	%	97.64

Figure 4.8 shows the heat balance plot for the heat balance error analysis demonstrated in Table 4.2.

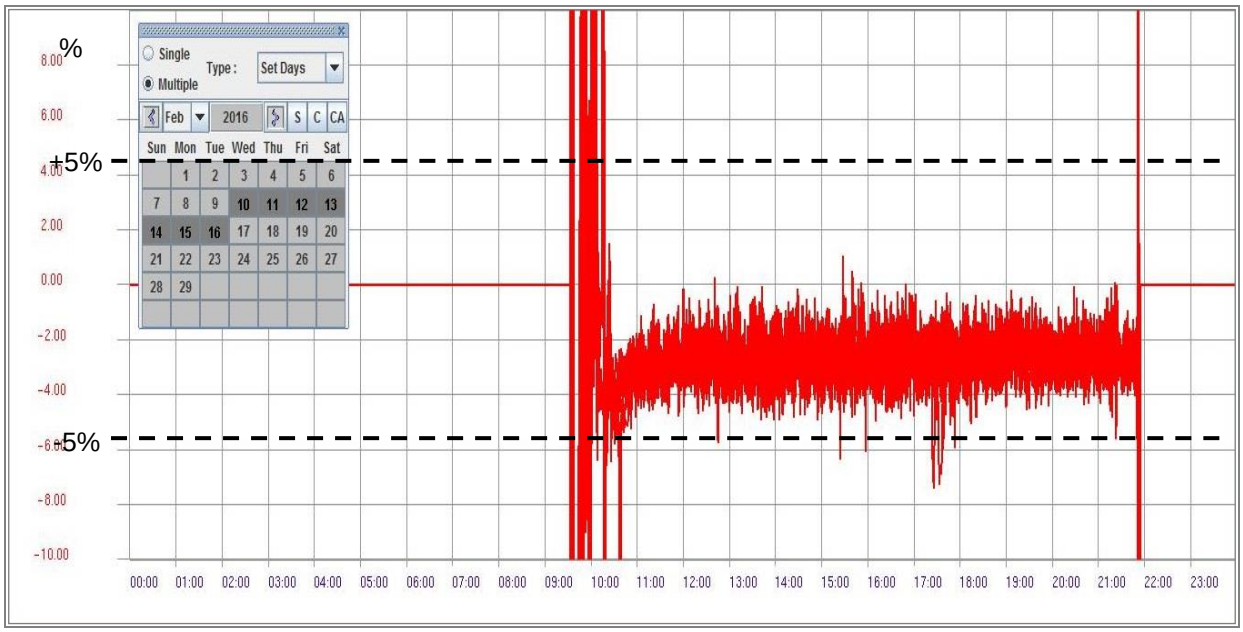


Figure 4.8: *System header level heat balance plot*

The heat balance results at system level show that 80% and above of data points collected fall within ±5% during the audit period.

4.5 Benchmarking

4.5.1 Codes and Standards

For BCA Green Mark for Existing Non-Residential Buildings (Version 3), the minimum design system efficiency are as follows:

(a) For buildings using water-cooled chilled-water plant

BCA Green Mark Rating	Building Cooling Load (RT)	
	< 500	≥ 500
	Efficiency (kW/RT)	
Certified	0.85	0.75
Gold	0.80	0.70
Gold^{Plus}	0.75	0.68
Platinum	0.70	0.65

(b) For buildings using air-cooled chilled-water plant or unitary air-conditioner

BCA Green Mark Rating	Building Cooling Load (RT)	
	< 500	≥ 500
	Efficiency (kW/RT)	
Certified	0.85	0.75
Gold	0.80	0.70
Gold^{Plus}	0.75	0.68
Platinum	0.70	0.65

Besides having an efficient chilled water plant / system, greater potential savings can be achieved with an efficient air-side system. BCA has extended its performance and M&V standards to air-side systems to achieve a verifiable minimum performance for the building's entire air-conditioning system (Author: Lee EL; Toh ES; T. Hartman, "Improving Commercial Buildings Energy Performance", ASHRAE Journal, November 2016).

The table below shows the minimum design total system efficiency (DSE) under the BCA Green Mark 2015 criteria (GM NRB:2015):

Air-cooled chilled water systems:

BCA Green Mark Rating	Peak Building Cooling Load (RT)		Remarks
	< 500 RT	≥ 500 RT	(η_c, η_a) shall meet their respective thresholds. η_c: System kW/ton excluding the air distribution equipment η_a: Air distribution equipment kW/ton $\eta_t = \eta_c + \eta_a$
	Minimum DSE (kW/RT): η_t (η_c, η_a)		
Gold	NA (0.9, NA)	NA (to be assessed on case by case basis)	
Gold^{PLUS}	1.10 (0.85, 0.25)		
Platinum	1.03 (0.78, 0.25)		

Water-cooled chilled water systems:

BCA Green Mark Rating	Peak Building Cooling Load (RT)		Remarks
	< 500 RT	≥ 500 RT	(η_c, η_a) shall meet their respective thresholds. η_c: System kW/ton excluding the air distribution equipment η_a: Air distribution equipment kW/ton $\eta_t = \eta_c + \eta_a$
	Minimum DSE (kW/RT): η_t (η_c, η_a)		
Gold	NA (0.75, NA)	NA (0.68, NA)	
Gold^{PLUS}	0.95 (0.7, 0.25)	0.9 (0.65, 0.25)	
Platinum	0.93 (0.68, 0.25)		

4.6 Case Studies

4.6.1 Good Practices

In order to ensure accuracy of the measurement data and results, it is important that installation of instruments shall be in accordance to the guidelines recommended by the manufacturers.

Immersion type temperature sensor

- Insufficient immersion of temperature probe will cause measurement error due to the effect of heat conduction along the steel stem.
- Recommended minimum immersion length = 20 x Diameter of steel stem (d) + sensor length (l)
- From a practical approach, it is better to fully immerse the stem to between 1/3 to 2/3 of pipe diameter.

Electromagnetic/ Ultrasonic flow meter

- Flow meter must be mounted at the required straight pipe length as per manufacturer guidelines.
- The transducers of ultrasonic flow meters must be placed at the spacing provided by the manufacturer.

4.6.2 Common Pitfalls

Some of the common pitfalls are highlighted below.

a. Power meters that are not integrated with CT may be prone to error due to wrong settings. For example, an energy audit revealed that power measurement error existed in BAS for 15 years because of a wrong CT ratio setting.
b. Temperature sensor accuracy has drifted. This may be caused by RTD/Thermistors drift due to vibration or data logger electronics drift.
c. Flow meter installed at turbulent flow location.

5 Measurement and Analysis of AHUs, FCUs and Mechanical Ventilation Systems

Introduction

“It is not possible to improve standards if we do not bother enough to measure accurately and continuously.”
“Energy efficiency does not happen by chance and no one cares much to improve when one is not being measured and rewarded.”

These two statements sum up the challenge of improving Singapore’s airside energy efficiency (EE) today. It is evident that there is hardly any measurement and verification (M&V) of airside EE performance and there lies the root of the poor performance. Some of the fundamental barriers to airside EE improvement is a lack of education on the importance of airside EM&A, technical knowledge to conduct EM&A and the cost of EM&A.

The airside system typically consumes up to 20% of a commercial building energy. The average airside operating energy efficiency is estimated to be about 0.40 W/CMH. The SS553 minimum standard for airside efficiency for a Constant Volume System is 0.47 W/CMH. Based on energy audits done by author, energy efficiency of AHUs that are not operated and/or maintained properly can be worse than 1.0W/CMH. Therefore, in the absence of EM&A, operating efficiency can deteriorate to as bad as 1.0W/CMH or about 10 times that of a very energy efficient airside of 0.10 W/CMH.

The airside system is the main determinant of the Indoor Air Quality (IAQ). It controls the indoor dry-bulb temperature, the indoor relative humidity, the air velocity, the amount of outside air ventilation and also provides filtration of particulates in the air. IAQ in turn has a major impact on occupant health and productivity.

Therefore, it is very important for building owners, M&E consultants and ESCOs to have the awareness and knowledge to carry out effective airside EM&A to ensure that the buildings have optimal airside energy efficiency and IAQ for the life of the building.

Learning Outcomes

Participants will be able to:

i. Acquire Level I & Level II skills in AHU/FCU EM&A
ii. Appreciate the depth of Level III M&A and be able to assess the outcome of Level III audits

5.1 Level I Audit For AHUs / FCUs and Ventilation Fans

The scope of work for level I audit are as follows:

Gather operating and design data

Gather and summarise the airside equipment as-built parameters. A sample template is shown below:

s/n	Designation
01	Location
02	Total cooling capacity (kW)
03	Year installed
04	Brand / model
05	Sensible cooling capacity (kW)
06	Airflow (CMH)
07	Air on-coil DB/WB (^oC)
08	Air off-coil DB/WB (^oC)
09	Coil air pressure drop (Pa)
10	Coil water pressure drop (kPa)
11	CHW flow rate (L/s)
12	CHW supply and return temperature (^oC)
13	ESP (pa)
14	TSP (pa)
15	Motor size (kW)
16	Input power (kW)
17	Fan static efficiency (%)
18	Motor efficiency (%)
19	Filter type
20	Filer efficiency
21	Compute design efficiency (kW/RT)
22	Compute design efficiency (W/CMH)
23	Compute floor area served by unit
24	Compute design cooling intensity (W/m^2)
25	Compute air-change (#/H)

Conduct Level I Audit for AHUs and FCUs

During the level I audit for AHUs / FCUs, you may use the checklist below as a guide to spot areas of wastages and/or inefficiencies.

Checklist for Level I Audit for AHUs/FCUs

s/n	Description
01	Is the area served by AHU/FCU thermally comfortable?
02	Is room temperature set-point sensible?
03	Is room temperature sensor location sensible?
04	Is room temperature reading sensible?
05	Is supply air temperature sensible?
06	Check & record CHW control valve position?
07	Is there VSD?
08	Check & record VSD speed?
09	Is VSD speed set-point sensible?
10	Verify that CHW control valve is working by varying set-point
11	Verify that VSD is working by varying set-point
12	Check and record filter condition
13	Check and record coil condition
14	Check and record fan condition (Belt tension, pulley alignment)
15	Check and record motor condition
16	Check and record drain pan condition
17	Check for any excessive CHW pressure drop e.g. valve throttling, sharp pipe bends
18	Check for any excessive air pressure drop e.g. damper throttling, sharp duct bends
19	Is control logic sensible?
20	Check & record duct cleanliness
21	Is there any ventilation demand control
22	Check that CHW control valve closes when AHU/FCU is turned off
23	Check AHU on/off schedule and verify that unit is following the schedule
24	Check frequency of filter change and specification of filters

Conduct Level I Audit for Ventilation Fans

During the level I audit for ventilation fans, you may use the checklist below as a guide to spot areas of wastages and/or inefficiencies.

Checklist for Level I Audit for Ventilation Fans

s/n	Description
01	Is the area served by fans thermally comfortable?
02	Is room temperature set-point sensible?
03	Is room temperature sensor location sensible?
04	Is room temperature reading sensible?
05	Is supply air temperature sensible?
06	Is there VSD?
07	Check & record VSD speed?
08	Is VSD speed set-point sensible?
09	Verify that VSD is working by varying set-point
10	Check and record fan condition (Belt tension, pulley alignment)
11	Check and record motor condition
12	Check for any excessive air pressure drop e.g. damper throttling, sharp duct bends
13	Is control logic sensible?
14	Check & record duct cleanliness
15	Is there any ventilation demand control?
16	Check fan on/off schedule and verify that unit is following the schedule

Prepare Level I audit report

The level I audit report for AHUs/FCUs and Ventilation Fans should encompass the following:

- Summary of findings and recommendations
- Report any IAQ issues that require attention
- Report any obvious energy wastages or inefficiencies
- Report any housekeeping maintenance issues
- Report any equipment or instrument failures that require repair
- Report improvement measures that have been carried out
- Report any IAQ and ECMs matters that merit further evaluation in level II audit

5.2 Level II Audit of AHUs / FCUs and Ventilation Fans

The scope of work for level II audit may vary, often depending on the findings from level I audit. Level II audit attempts to verify and quantify performance issues or opportunities for energy conservation measures by carrying out spot measurements or short term measurement using fairly simple instruments. Some examples of level II audit scope of work are illustrated in the following sections.

Verification of Space Temperature and %RH

Verify and quantify any spaces that are over cooled using data loggers that record dry bulb temperature and relative humidity at regular intervals such as every 5 minutes for a period of about 1 week.



Figure 5.1: *Portable Temperature and %RH Logger*

Verification of Equipment Operating Hours

Verify and quantify any spaces that have excessive operating hours by using loggers that record operating amps for AHUs/FCUs and Ventilation Fans.

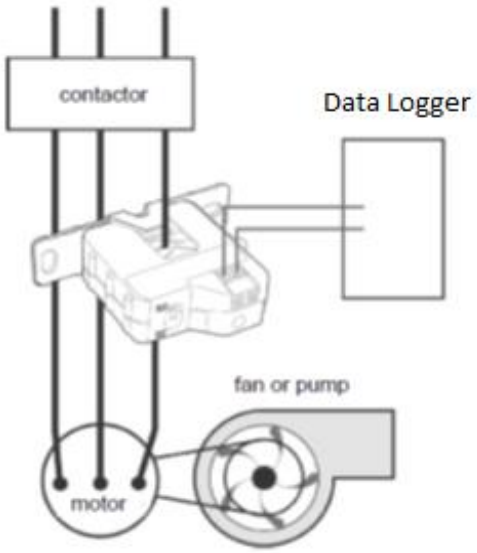


Figure 5.2: *Measuring Equipment Operating Hours*

Verification of AHU/FCU and Ventilation Fan Air-changes

Verify and quantify any excessive AHU/FCU air change by measuring airflow using an anemometer. Dividing the airflow in CMH by the volume of air condition space in m^3 will give the number of air changes per hour.



Figure 5.3: *Measuring AHU/FCU and Ventilation Fan Airflow*

Verification of Outside Air Ventilation Rates

Verify and quantify any excessive outside air ventilation by measuring the airflow of outside air intake using an anemometer. Dividing the outside air flowrate by the floor area will yield the ventilation rate in L/s per m^2.

Verification of Filter and Coil Pressure Drops

Verify AHU/FCU filter and coil pressure drop by measuring the differential pressure using data logger for variable speed fans or spot measurements for constant speed fans.

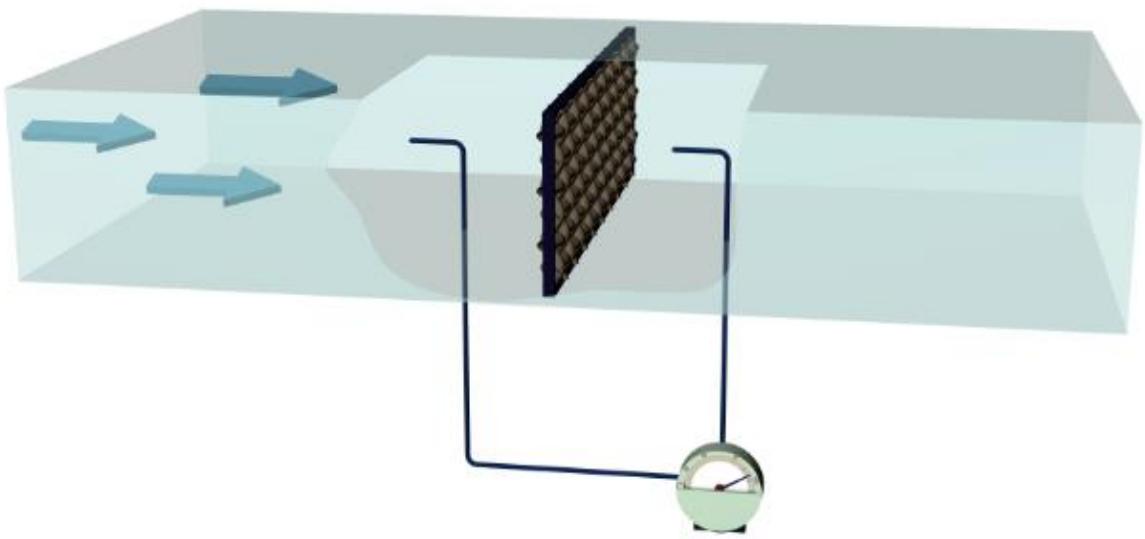


Figure 5.4: *Measuring Filter Pressure Drop*

Verification of Power Inputs

Verify and quantify all major sub system energy flow using power meters that record kW and amps at 15 minute intervals for a period of at least 1 week.

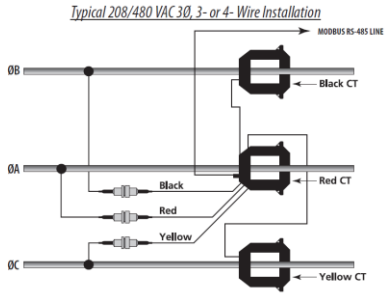


Figure 5.5: *Measuring Power Input*

Verification of Indoor CO_2 and Carpark CO Concentration

Verify and record CO_2 concentration in the occupied space by spot measurement using CO_2 sensor. The number of sampling points can take reference from Ministry of Environment's Guidelines for Good Indoor Air Quality in Office premises.

1 Assessment of indoor air quality parameters

(a) Sample position

The sampling probe should be located between 75 and 120 cm from the floor at the centre of the room or an occupied zone.

(b) Number of sampling points

Indoor
At least one sample should be taken from each floor or from each area serviced by a separate air handling unit. For large floor spaces, the guidelines for the minimum required number of sampling points are as follows:

Area of building (m^2)	Minimum number of sampling points
3,000 - <5,000	8
5,000 - <10,000	12
10,000 - <15,000	15
15,000 - <20,000	18
20,000 - <30,000	21
30,000 or more	25

Outdoor
At least two samples should be taken at the entrance to the building or at the entrance of the fresh air intake.

Figure 5.6: *IAQ Measurement Sampling Points*

(Source: National Environment Agency_Office_IAQ_Guidelines)

Verify and record CO concentration in carparks using CO sensor. According to SS553-2009, the acceptable carbon monoxide concentration is below 25 ppm averaged over an hour period.

Collate all the measurements and analyse the performance by use of tables and charts.

Prepare Level II audit report

The Level II audit report for AHUs/FCUs and Ventilation Fans should encompass the following:

- Summary findings and recommendations
- Charts and tables summarising the measurements
- Comparison to design figures and benchmark figures to quantify the level of wastage and efficiency
- Recommendations for ECMs and estimates of potential energy conservation
- Estimation of investment cost and financial return on investment.
- Report any IAQ and ECM matters that merit further evaluation in Level III audit

5.3 Examples of Level III Audit for AHUs, FCUs and Ventilation Fans

A level III audit involves continuous and accurate measurement of airside system performance and efficiency. The typical audit duration is 1 week and data recorded at 1 to 5 minute intervals. For examples of level III audit results for airside equipment, refer to section 5.6

5.4 Instruments

The instruments used for airside energy measurement can be group broadly into 3 categories:

a. Air side measurement
b. Water side measurement
c. Power measurement

For water side and power measurement, please refer to the topic on chilled water system in Chapter 4. This chapter will focus on air side measurement.

Besides using the metric of kW/RT for quantifying the performance of AHUs and FCUs, another metric is W/CMH. For ventilation fans where no cooling is involved, W/CMH will be the metric of efficiency. The measurement of kW/RT was addressed in Chapter 4.

The primary focus of this chapter will be measurement of airflow. There are several types of airflow meters used in the industry. The common ones are:

- Pitot tube
- Pitot array
- Thermal dispersion duct probe
- Handheld Hotwire Anemometer
- Handheld Propeller Fan Anemometer

Pitot-Static Tube Operating Principle

It works by using a manometer-like attachment to measure the difference in pressure between two points in a pipe, which makes it possible to determine the velocity of the fluid in the pipe using Bernoulli's equation.

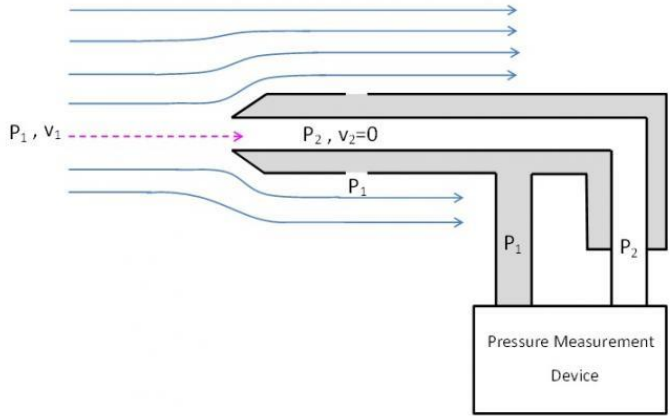


Figure 5.7: *Pitot-Static Tube*

The air velocity is computed according to the formula below:

$$V_1^2 = \frac{2\,(P_1 - P_2)}{\rho_1}$$

where,

P_1 = Air total pressure (pa)

P_2 = Air static pressure (pa)

ρ_1= Air density (kg/m^3)

In order to obtain a representative average velocity in a duct, it is necessary to locate each traverse point accurately. It is recommended that the number of traverse points increase with increasing duct size.

Pitot-Static Array Operating Principle

The Pitot-Static Array typically consists of a multi-point, self-averaging pitot traverse station with integral air straightener honeycomb cell that is capable of continuously measuring ducted airflow.



Front View Back View

Figure 5.8: *Pitot-Static Array*

(Source: Kele & Associates Pte Ltd)

Thermal Dispersion Duct Probe Operating Principle

Thermal Dispersion technology uses the principle of measuring the heat loss, or cooling effect, of a fluid flowing across a heated cylinder. A typical flow element configuration uses two RTDs, sheathed in thermowells, separated by a gap. Heat is applied internally to one RTD relative to the other, creating a differential temperature between the two. This differential temperature is greatest at no flow conditions and decreases as flow increases, cooling the heated RTD.

Using the relationship between flow rate and cooling effect, Thermal Dispersion technology can provide a highly repeatable and accurate measurement of air flow rates.

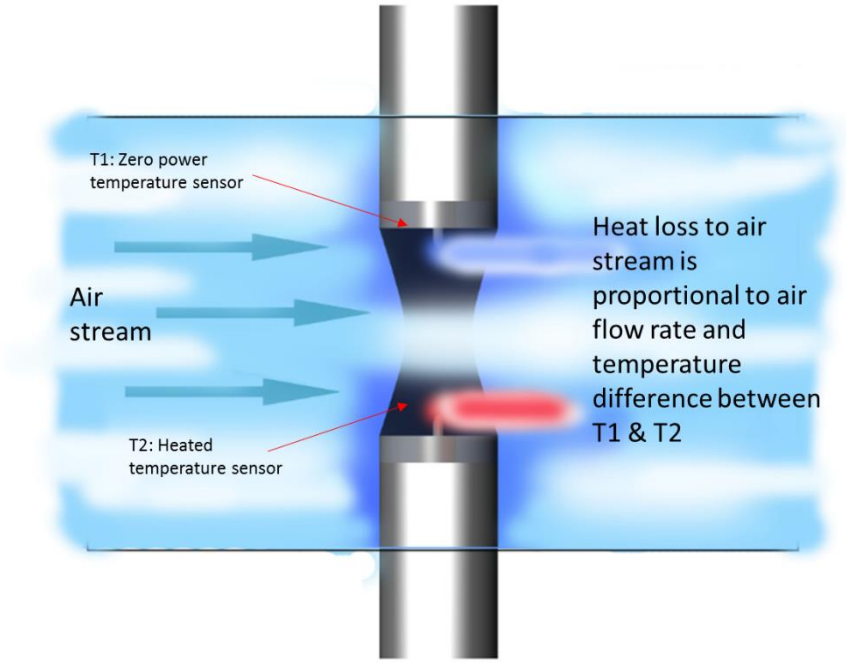


Figure 5.9: *Thermal Dispersion Anemometer*

Hot Wire Anemometers Principle of Operation

The Hot-Wire Anemometer is the most well-known thermal anemometer. It measures a fluid velocity by noting the heat convected away by the fluid. The core of the anemometer is an exposed hot wire either heated up by a constant current or maintained at a constant temperature (refer to the schematic below). In either case, the heat lost to fluid convection is a function of the fluid velocity. By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with convective theory.

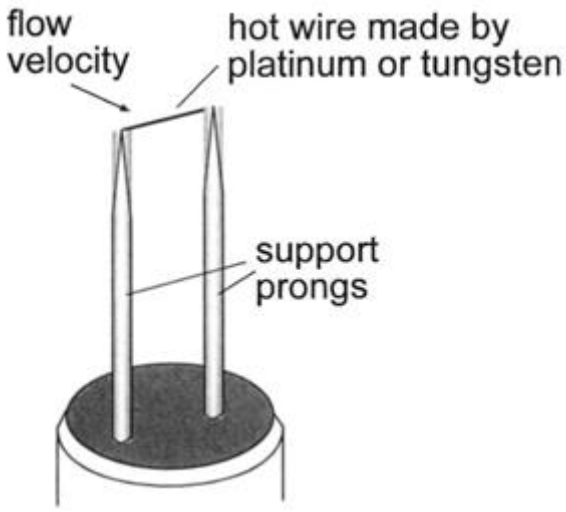


Figure 5.10: *Hot Wire Anemometer*

Vane/Propeller Anemometer Principle of Operation

Propeller anemometer uses fan blades which spin as the air passes through it. The fan blades turn a tiny generator which is connected to an electronic circuit that measures the frequency of the spinning blades which is co-related to the airflow speed.

Comparison of Various Anemometers

Measurement Technologies	Application	Range (m/s)	Precision	Limitations
Pitot array, self-averaging diff pressure	In-duct assemblies	3 to 50	± 2 to 40% of reading	• Performance depends heavily on quality and range of differential pressure transmitter. • Very susceptible to measurement errors caused by duct placement or dust-clogged pitot tubes. • Pressure drop penalty of about 10pa (@5m/s) due to air straightener • The array must be custom-built to suit the duct size. • Straight duct: Before 2D, after 1/2 D with integrated air straightener.
Thermal dispersion duct probe using thermistor	In-duct assemblies	0.1 to 50	± 2 to 20% of reading	• Cost increases with number of sensor assemblies in array. • Affected by thermal changes in air • Affected by alignment with flow direction • The duct probes have to be custom-built to suit the duct size. • Straight duct: Before 3.5D ,After 2D
Handheld Hotwire Anemometer	In-duct assemblies	0.25 to 50	± 2 to 40% of reading	• Requires accurate calibration at frequency interval.

Measurement Technologies	Application	Range (m/s)	Precision	Limitations
				• Severely affected by alignment with flow direction • Measurement tends to fluctuate widely because of point source measurement. • Affected by thermal change in air. • Manual spot reading only and labour intensive • Straight duct: Before 3.5D ,After 2D
Handheld Vane/Propeller Anemometer	At Filter face or coil face area	3 to 50	± 1% to 10% of reading	• More stable than point-source measurement due to impeller averaging effect • Affected by alignment with flow direction • Manual spot reading only and labour intensive • Need access to filer face area or coil face area

5.5 Data To be Measured

Recommended airside data to be measured are as follows:

Airside

Parameters to be Measured	**Recommended duration and frequency for audit**
Airflow	Manual spot measurement
Room air temperature and RH%	Continuous measurement for 1 week at 5 minute intervals
Return air temperature and RH%	Continuous measurement for 1 week at 5 minute intervals
Outside air temperature and RH%	Continuous measurement for 1 week at 5 minute intervals
Supply air temperature and RH%	Continuous measurement for 1 week at 5 minute intervals
Fan Static Pressure	Manual spot measurement

Recommended waterside data to be measured is as follows:

Waterside system

Parameters to be Measured	**Recommended duration and frequency for audit**
Chilled water flow rate	Continuous measurement for 1 week at 5 minute intervals
Chilled water supply temperature	Continuous measurement for 1 week at 5 minute intervals
Chilled water return temperature	Continuous measurement for 1 week at 5 minute intervals
Chilled water pressure drop	Continuous measurement for 1 week at 5 minute intervals

Recommended electrical side data to be measured is as follows:

Electrical side

Parameters to be Measured	**Recommended duration and frequency for audit**
Input power	Continuous measurement for 1 week at 5 minute intervals

Parameters to be computed

The following data can be computed from the measured data as follows:

- Chilled water cooling capacity
- Chilled water delta T
- Airside delta T
- Efficiency in kW/RT
- Efficiency in W/CMH

For permanent measurement system, it is recommended to have continuous measurement at 5 to 15 minutes intervals.

5.6 Data Analysis

A level III audit will produce a lot of data which will require organisation into tables or graphs for analysis and presentation. Examples of tabulations and graphical representation are shown below:

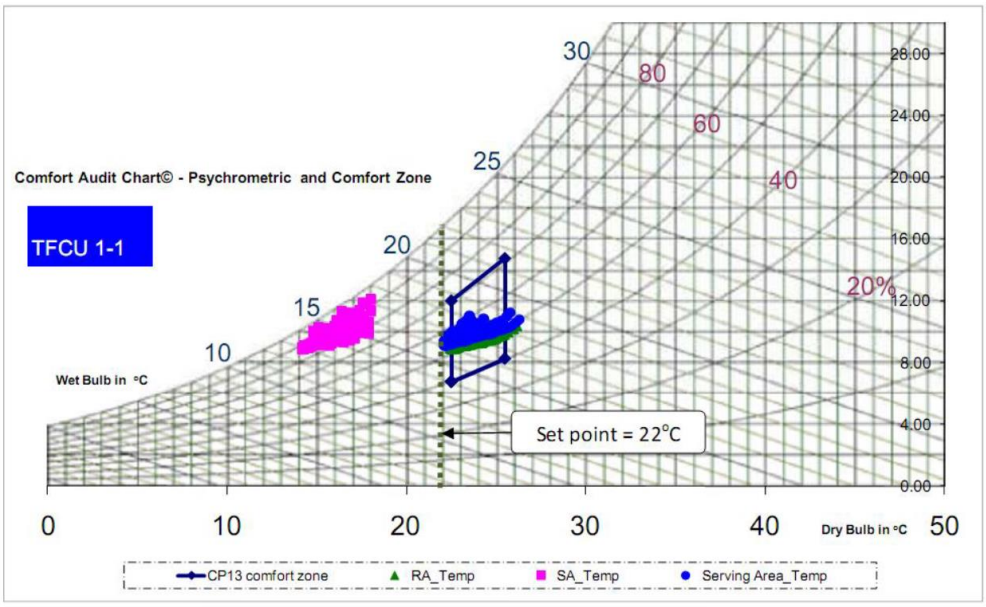


Figure 5.11: *Plot of Indoor, Supply and Outside Air Conditions*

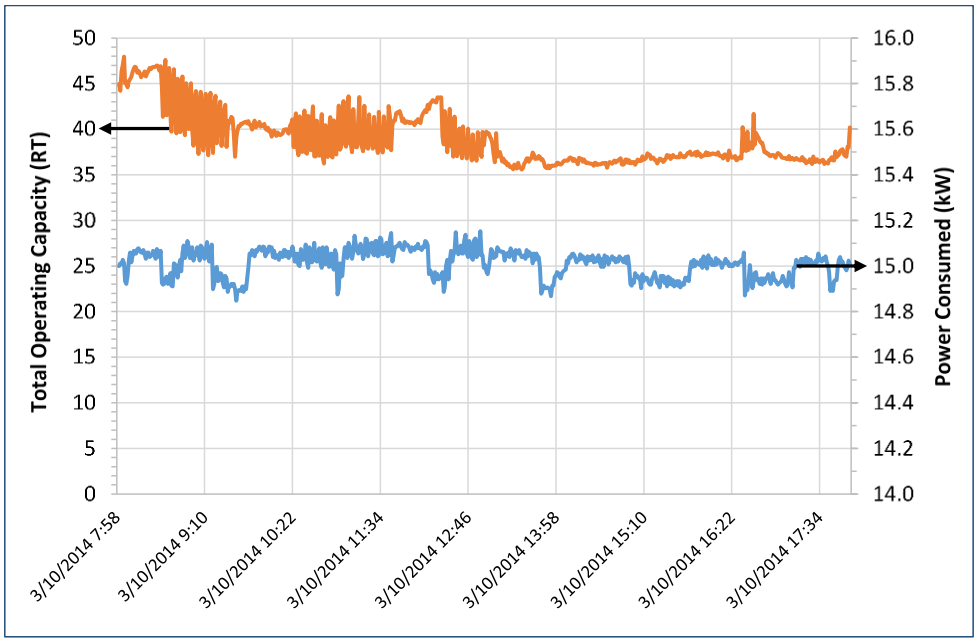


Figure 5.12: *Graph of AHU RT and Power*

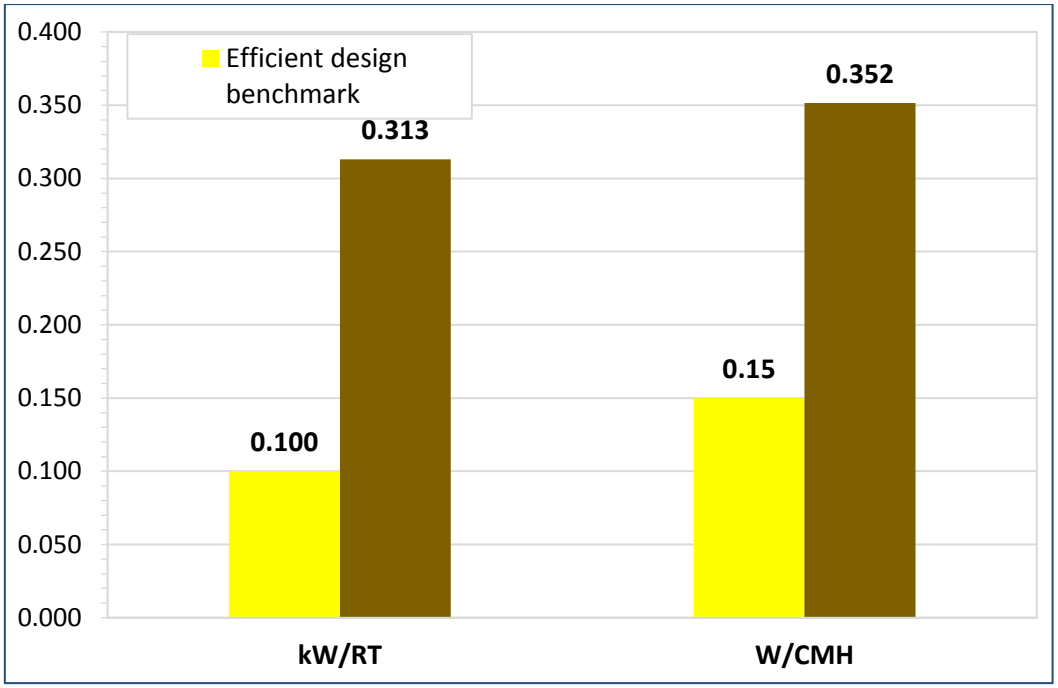


Figure 5.13: *Graph of AHU Efficiency*

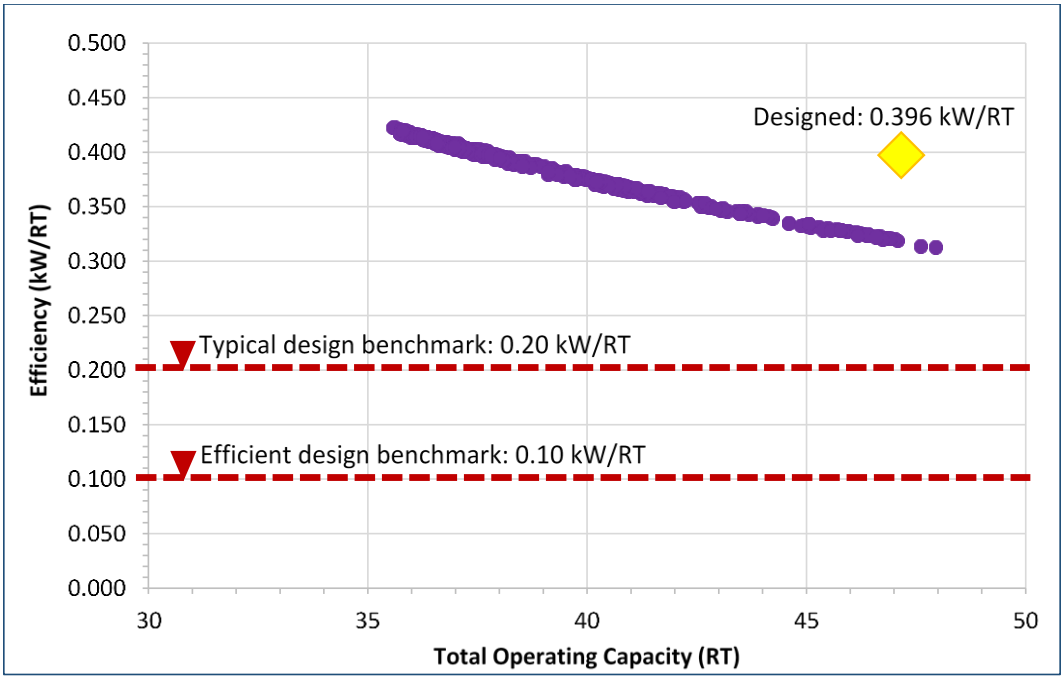


Figure 5.14: *Graph of AHU Efficiency vs RT*

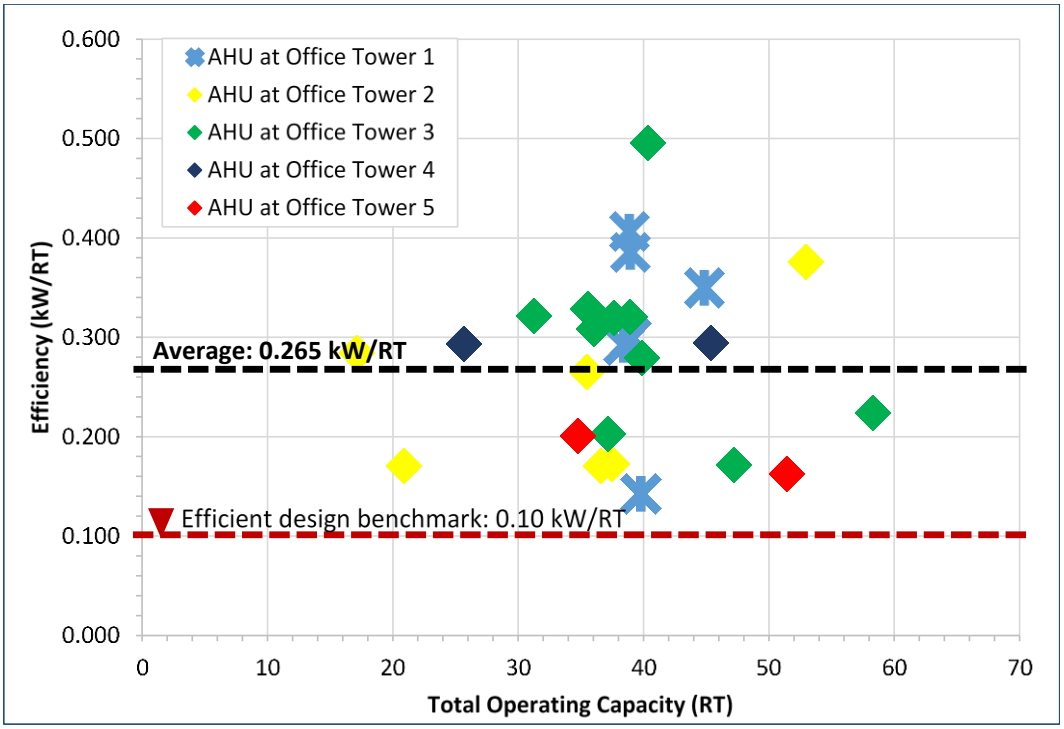


Figure 5.15: *Graph of AHU Efficiency Vs RT*

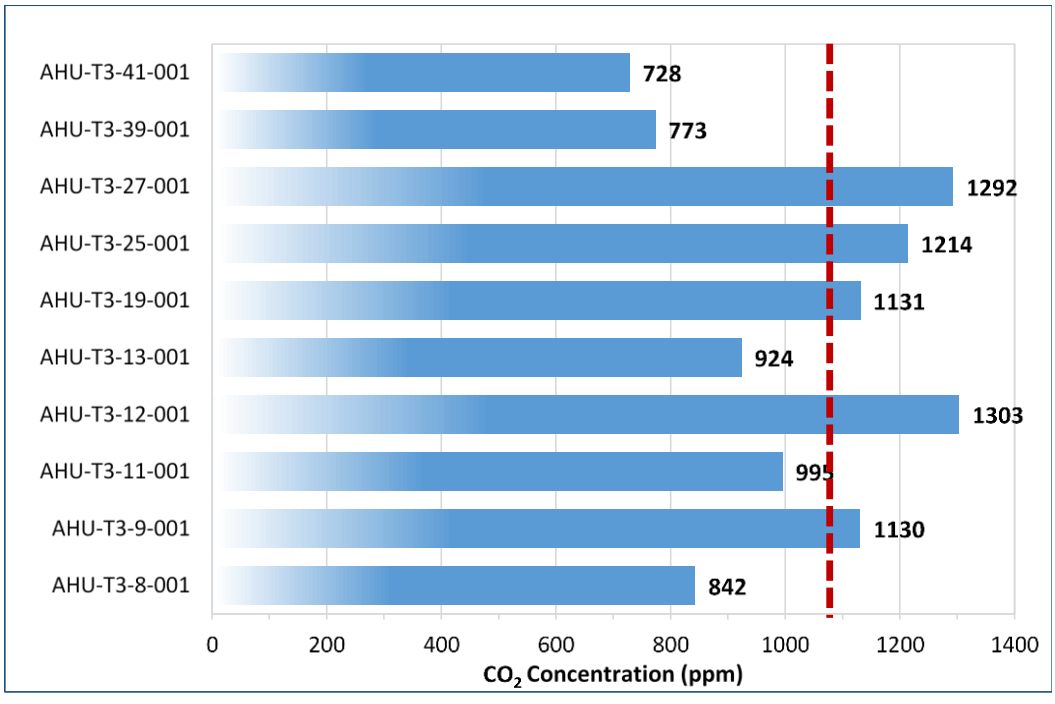


Figure 5.16: *Plot of CO_2 Measurements*

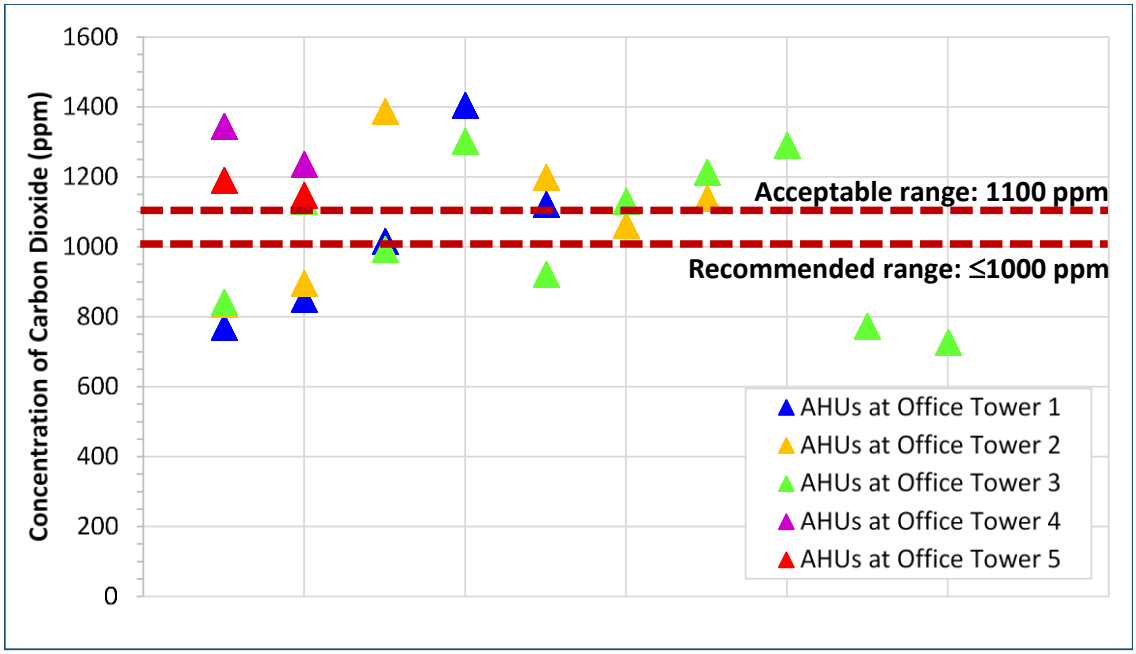


Figure 5.17: *Graph of CO_2 measurements*

Example of Summary of energy saving calculations for AHU replacements

No.	Description	Unit	Value
1	AHU peak operating tonnage	RT	5000
2	Annual AHU total operating tonnage	RT/year	16,780,197
3	Average existing AHU operating performance	kW/RT	0.265
4	Proposed new AHU operating performance	kW/RT	0.10
5	Improvement in operating performance	kW/RT	0.165
6	Power reduction	kW	825
7	Annual electricity consumption saved	kWh/year	2,768,733
8	Annual electricity consumption saved (@ S$0.20/kWh)	S$/year	553,747
9	Other savings due to AHU parasitic load reduction*	S$/year	121,880
10	**TOTAL ELECTRICITY CONSUMPTION SAVED**	**S$/year**	**675,627**

**Example of parasitic load includes heat dissipated by AHU motor*

Example of Summary of spot power measurement for MV fans in operation (Tower 1 – 5)

Location of MV Fans	Nos. of Measured MV Fans	Power Consumed (kW)		
		Minimum	Average	Maximum
Office Tower 1	18	0.32	1.73	5.52
Office Tower 2	21	0.06	1.67	9.74
Office Tower 3	12	0.21	2.58	8.39
Office Tower 4	12	0.24	3.26	12.27
Office Tower 5	6	0.06	2.02	10.10

5.7 Benchmarking To Standards and Best Practices

Comparison of measuring AHUs and FCUs efficiency using W/CMH and kW/RT

The energy efficiency of AHUs and FCUs can be measured in either W/CMH or kW/RT. Both metrics have its advantages and disadvantages.

Energy efficiency for AHUs, FCUs and Ventilation Fans in SS553:2016:

Constant volume	Variable volume
Allowable nameplate motor power per unit volume flow rate of air	
0.47 W/CMH or 1.7 kW/m^3/s	0.67 W/CMH or 2.4 kW/m^3/s
0.47 W/CMH is equivalent to (0.47 W/ m^3/h) x 3600 (m^3/h / m^3/s) x 1/1000 (kW/W) = 1.7 kW/m^3/s	0.67 W/CMH is equivalent to (0.67 W/ m^3/h) x 3600 (m^3/h / m^3/s) x 1/1000 (kW/W) = 2.4 kW/m^3/s

Individual VAV fans with motors 7.4 kW and larger shall meet one of the following requirements:

a. Be driven by an electrical variable speed drive;

b. Have other controls and devices for the fan that will result in fan motor demand of less than 30% of design wattage at 50% of design air volume when static pressure setpoint equals one-third of the total design static pressure based on manufacturer's certified fan data.

Energy efficiency for AHUs, FCUs and Ventilation Fans in BCA Green Mark for Existing Non-Residential Building V-3.0 (GM ENRB-V3):

Allowable nameplate motor power	
Constant volume	**Variable volume**
0.47 W/CMH	0.74 W/CMH

Energy efficiency for AHUs, PAHUs and FCUs (air distribution system) in BCA Green Mark for New Non-Residential Building (GM NRB: 2015):

The energy efficiency of the air distribution components, which include AHUs, PAHUs and FCUs, shall not exceed 0.25 kW/RT for BCA Green Mark Gold^{PLUS} and Platinum rating.

The advantages of computing the efficiency of AHU/FCU in kW/RT:

- Can be easily added to chilled water system kW/RT to derive the total air + water efficiency
- Can measure the airside power consumption and utilise the chilled water system RT to obtain the total airside kW/RT.
- kW and RT can be measured very accurately. Uncertainty of ±5% is easily achievable.

The disadvantages of computing efficiency of AHU/FCU in kW/RT:

- The kW/RT may fluctuate very widely if the RT has wide variation especially for Constant Air Volume System.
- kW/RT will not be valid if there is no cooling, for example during economizer mode or purging mode.
- To measure RT accurately, hotapping of the CHW pipe is required for the insertion of temperature probe. This will increase the cost.

The advantages of computing efficiency of AHU/FCU in W/CMH:

- The W/CMH is meaningful even when there is little or no cooling.
- W/CMH is a direct measure of air delivery efficiency independent of cooling load.
- Applicable during economizer mode or purge mode.

The disadvantages of computing efficiency of AHU/FCU in W/CMH:

- Airflow measurement has high uncertainty.
- There is usually insufficient straight duct for accurate air flow measurement.

Energy Efficiency Benchmark for AHU/FCU in kW/RT:

Based on the author's experience on past energy audits, the average efficiency of AHUs is approximately 0.28 kW/RT and the average efficiency of PAHUs is approximately 0.15 kW/RT. The best practice guideline for AHU and PAHU efficiencies are 0.10 and 0.05 kW/RT respectively.

5.8 Good Practices and Common Pitfalls

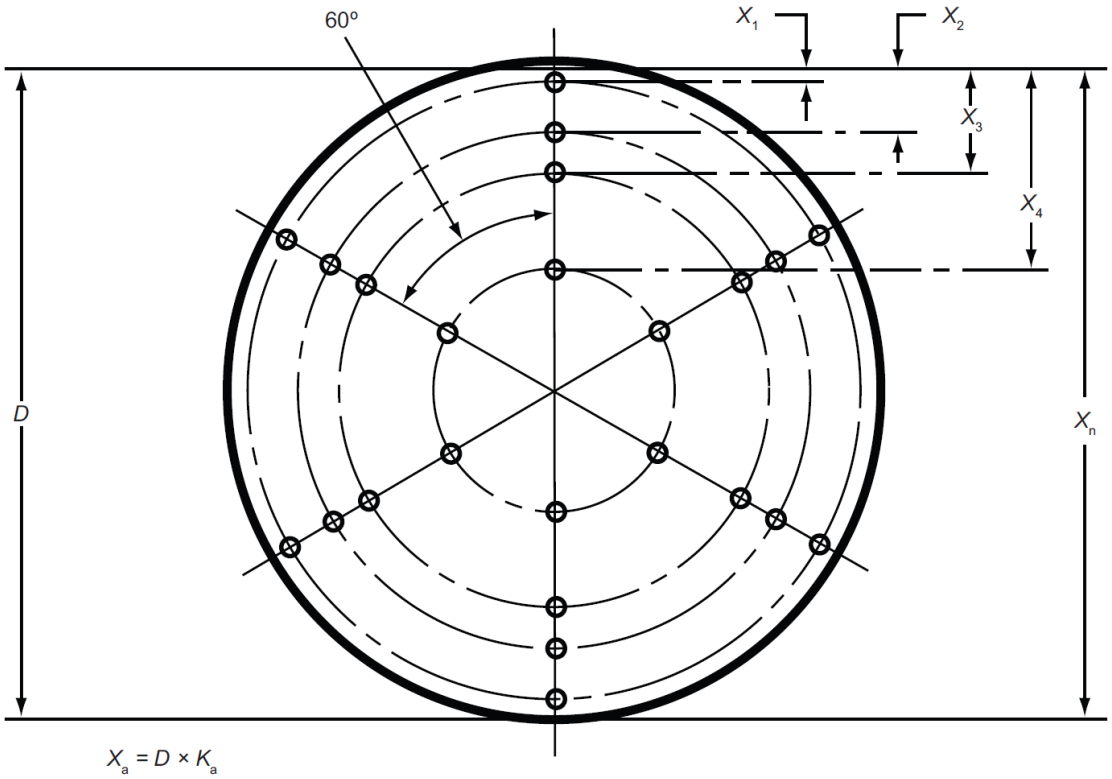
Good Practices

It is a good practice to measure the airside efficiency continuously so that we can have continuous data to track, maintain and even improve the airside system efficiency over its life cycle.

In BCA Green Mark Version 2015 for New Non-residential Building (GM NRB:2015), BCA is requiring minimum standards for Total Air-conditioning system efficiency i.e. Airside + waterside kW/RT. The pre-requisite for the minimum design total system efficiency (DSE) of water-cooled chilled water systems (peak cooling load ≥ 500 RT) for Platinum and Gold^{PLUS} level is 0.90 kW/RT. The standard also requires continuous measurement of airside kW and waterside RT to derive the airside kW/RT over a 1 week period.

For airflow measurement, it is necessary to pay attention to the manufacturer's minimum required length of straight duct before and after the flow meter. Installing airflow meter at turbulent location will lead to very high level of uncertainty in the measurement.

For measuring of airflow using the transverse method, there must be enough measurement points across the cross section of the duct to obtain accuracy. Below are recommended distribution points from AMCA Publication 203: Field Performance Measurement of Fan Systems.

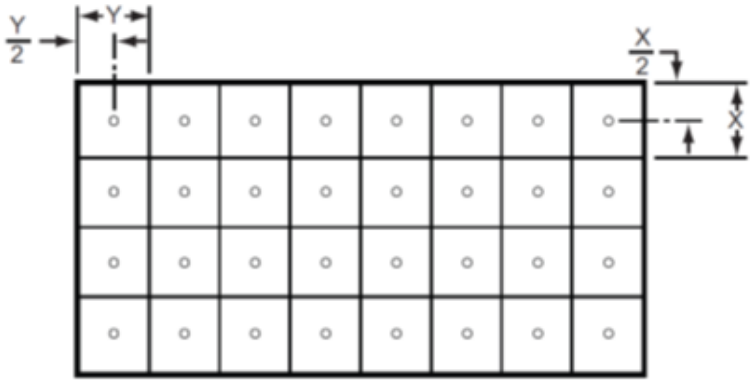


Where:
D is the inside diameter of the duct
K_a is the factor corresponding to the duct size and the traverse point location as indicated in the table below

INSIDE DIAMETER OF DUCT	NUMBER OF TRAVERSE POINTS IN EACH OF 3 DIAMETERS	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}
LESS THAN 8 ft.	8	.021	.117	.184	.345	.655	.816	.883	.979	—	—	—	—	—	—	—	—
8 ft. THROUGH 12 ft.	12	.014	.075	.114	.183	.241	.374	.626	.759	.817	.886	.925	.986	—	—	—	—
GREATER THAN 12 ft.	16	.010	.055	.082	.128	.166	.225	.276	.391	.609	.724	.775	.834	.872	.918	.945	.990

Figure 5.18: *Distribution of Traverse Points for Circular Ducts*

(Source: AMCA Publication 203: Field Performance Measurement of Fan Systems)



Distribution of Traverse Points for Rectangular Duct

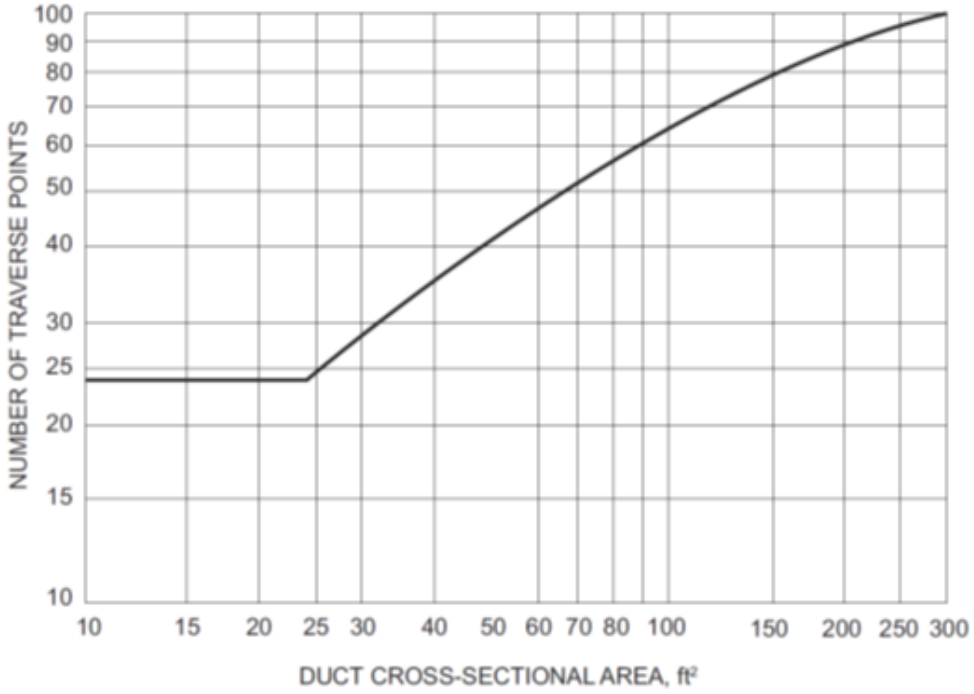
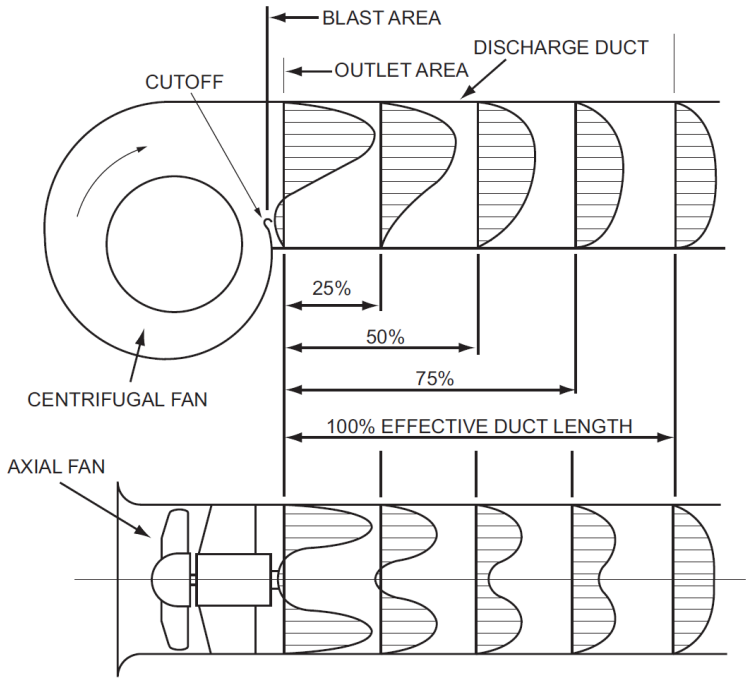


Figure 5.19: *Distribution of Traverse Points for Rectangular Ducts*
(Source: AMCA Publication 203: Field Performance Measurement of Fan Systems)

Common Pitfalls

One common pitfall of airflow measurement is taking measurements too near to fan discharge and suction. At fan discharge, take measurements after sufficient length of discharge duct for airflow to become fully developed. At fan suction, the measurement plane must be sufficiently away from the fan inlet. See figures below for recommendations according to AMCA Publication 203.



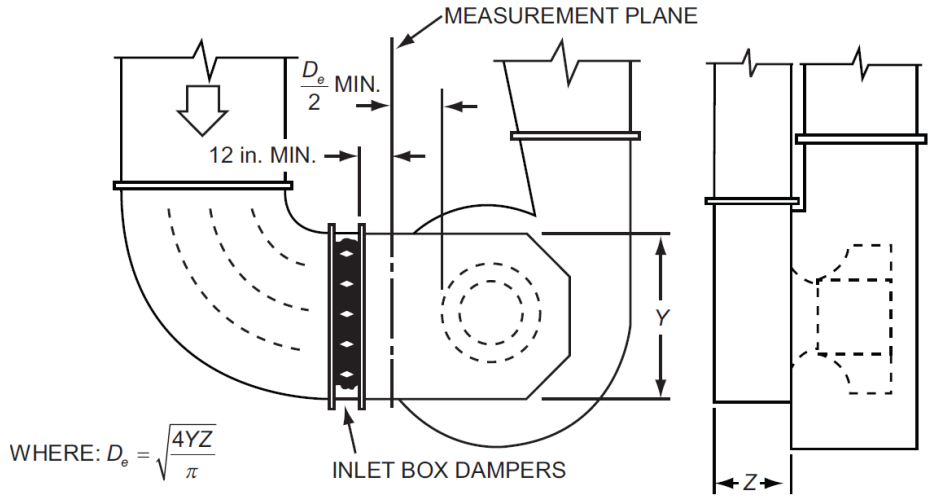
To calculate 100% effective duct length, assume a minimum of 2½ duct diameters for 2500 fpm or less. Add 1 duct diameter for each additional 1000 fpm.

Example: 5000 fpm = 5 equivalent duct diameters

If the duct is rectangular, with side dimensions equal to *a* and *b*, the equivalent duct diameter is equal to $(4ab/\pi)^{0.5}$

Figure 5.20: *Establishment of Uniform Velocity Profile in a Straight Length of Outlet Duct*

(Source: AMCA Publication 203: Field Performance Measurement of Fan Systems)



Note: The measurement plane should be located a minimum of ½ De from the inlet cone, but not less than 12 in. from the leaving edge of the damper blades.

Figure 5.21: *Measurement Plane for Fan Suction Airflow Measurement*

(Source: AMCA Publication 203: Field Performance Measurement of Fan Systems)

Another common pitfall is the use of average velocity pressure instead of root mean square. When measuring airflow using velocity pressure, the velocity pressure is the root mean square of velocity measurements made in the traverse plan and not the average.

The field measurement of a fan's performance is primarily to determine its efficiency and to determine the measures to improve its performance. However, if measurements were taken for the purpose of a fan acceptance test, then fan System Effect Factor (SEF) must be accounted for. SEF is a pressure loss which recognises the effect of fan inlet restrictions, fan outlet restrictions, or other conditions influencing fan performance when installed in the system. AMCA Publication 201, Fans and Systems, deals in detail with the effect of system connections on fan performance. It gives system effect factors for a wide variety of obstructions and configurations which may affect a fan's performance.

6 Lighting Systems

Appropriate lighting systems are essential for commercial buildings and industrial plants to ensure comfort, productivity and safety of the occupants. The lighting level or illumination level required in a space depends on the tasks performed in the space, type of space and other visual requirements. If the efficacy of the installed lamps is poor, only a small fraction of the input electrical energy to the lamps is converted into useful light and the remaining energy is converted into heat. Hence, poor efficacy lamps used in air-conditioning spaces increase the cooling load of the air-conditioning systems. Therefore, lighting systems should be designed carefully to achieve the required lighting level while using the minimum amount of electrical energy.

Learning Outcomes

Participants will be able to:

a. Understand important definitions associated with lighting systems
b. Understand lighting related requirements that are stipulated in SS 530: 2014 and SS 531
c. Acquire level I and 2 skills in lighting audit
d. Appreciate the depth of level III measurement and analysis
e. Assess the outcome of level III audits
f. Calculate lighting power density

6.1 Definitions

Important definitions associated with the lighting systems are:

Luminous flux: Luminous flux is defined as the quantity of light emitted by a lamp or light source. The SI unit of luminous flux is lumen. For example, a fluorescent lamp emits 2,400 lumens of light by consuming 36 W of electrical power.

Luminous efficacy: Luminous efficacy is the efficiency of a lamp or light source. Luminous efficacy is defined as:

$$Luminous efficacy = \frac{Luminous\ flux\ emitted\ by\ a\ lamp,\ lumen}{Power\ consumed\ by\ the\ lamp\ and\ ballast,\ W} \quad (6.1)$$

For example, the power consumption of the ballast (also called control gear) of the fluorescent lamp discussed above is 4 W. The luminous efficacy of the fluorescent lamp is 2400/(36+4) = 60 Lumens/W.

Illuminance: Illuminance (or lux level) is defined as the amount of the direct illumination on a surface area of one square metre. The SI unit of the illuminance is lux. Based on Singapore Standard SS531, the recommended lux levels for few selected areas are shown in Table 6.1.

Table 6.1: *Recommended lux levels (Based on SS531) for few selected areas.*

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

Lighting Power Density: Lighting power density is defined as the electric power consumption by the lamps and ballasts per unit floor area of the space.

$$Lighting\ \ power\ \ density = \frac{Power\ consumption\ by\ lamps\ and\ ballasts,\ W}{Floor\ area,\ m^2} \qquad (6.2)$$

Based on Singapore Standard SS530: 2014, the recommended maximum lighting power density values for few selected areas are shown in Table 6.2.

Table 6.2: *Lighting power density (Based on SS530: 2014) for few selected areas.*

Description	Maximum lighting power density based on SS530: 2014 (W/m^2)
Offices and class rooms	12
Lecture theatres	Refer to SS530 for full table
Auditoriums, concert halls	
Conference halls, Multi-purpose halls	
Jewelry, crystal shops	
Furniture, clothing and accessories, cosmetics, artwork shops	
Supermarket, sporting goods, hardware and stationery, pharmacy	
Restaurants	
Lift lobbies	
Stairs, escalators, travellators	
Corridors, circulation areas	
Carparks	
Electronic manufacturing and fine detail/assembly industries	
Storage areas	
Warehouses	7

6.2 Scope of Work for Level I to 3 Audits

Same as the audits for other energy consuming systems, a level I audit involves a brief survey of lighting systems of the building. During the level I walk through audit, types of lamps used, approximate number of lamps of each type and their typical power consumption, control strategies and lux level for different areas are assessed without any actual measurement or counting of lamps. This initial assessment helps to estimate the potential energy savings and provide cost estimates of low-cost or no-cost measures.

A more detailed survey of the lighting systems is conducted in level II audits. Normally, the level II audits do not include data logging, but may involve spot measurement of parameters such as power consumption of selected lamps and lux values at different areas. Level II audits of the lighting systems are able to identify and shortlist the areas or measures that have good

potential for savings. Hence, level II studies are useful for the allocation and better utilisation of the available resources for the measurements and data collection during the detailed audit.

Level III audits of the lighting systems involve more detailed measurements and field data collection, such as measurement of power of selected lighting circuits or selected types of lamps, types of ballasts used and their power consumption, counting the number and types of lamps, control strategies (on-off timing, daylight sensors, motion sensors, occupancy sensors, etc.), measurement of lux values for each typical area, study floor plan layout drawings and determine floor areas for different usages. Finally, engineering analysis is carried out using the collected data and information to determine the energy and cost saving opportunities, project implementation cost, and technical and financial feasibility analysis with higher level of confidence.

Common Pitfalls:

i. Electrical measurements of lighting circuits should be made for selected circuits that have only lighting loads. If other loads are on the circuits, the non-lighting loads should be isolated during the measurement or the non-lighting loads should be measured separately and subtracted from the measured power of the circuits.
ii. A lighting circuit should not be selected for the measurement of power if the lighting circuit contains different types of lamps. Otherwise, the lighting fixtures that contain other types of lamps should be de-lamped before the measurement of power of the lighting circuit.
iii. Number of de-lamped fixtures and non-operating fixtures should be identified during the lighting survey. A de-lamped fixture is not a non-operating fixture. Non-operating fixtures are those that are typically operating but have broken lamps, ballasts, and/or switches that are intended for repair. Fixtures that have been disabled or de-lamped or that are broken should be identified and reported.

6.3 Instruments

Lux meter: Lux meter is used to measure the illuminance or lighting level in lumen/m^2 or lux. The measurement can be trend logged or spot measurement. The accuracy of the lux meter is about ± 5%.

Power meter: Power meter is used to measure the power consumption of; (a) lighting circuits (that have only lighting loads), (b) selected types of lamps and (c) different types of ballasts.

The measurement of power could be spot measurement or trend logged at 1 to 5 second intervals for a period of about 1 hour. The accuracy of the power meter is ± 1% or better.

6.4 Data to be Collected

Data to be collected during the audit of lighting systems include:

i. Lighting levels (lux)
ii. Power consumed by lighting circuits or selected types of lamps
iii. Number and types of lamps and their power consumption
iv. Number and types of ballast and their power consumption
v. Lighted floor area and usage of spaces
vi. Lighting operating hours
vii. Lighting control strategies e.g. on-off timing, daylight sensors, motion sensors, occupancy sensors etc.

6.5 Data Analysis

Power Consumption: As a part of the data analysis, the trend logged power of the lighting circuits or typical lamps should be plotted so that the variation of power with time can be identified. Average power consumption of the lighting circuits should be calculated. If the lighting circuits contain similar type of lamps, the number of lamps connected with the circuits should be counted and average power consumption of each lamp can be calculated as:

$$Power\ of\ \ each\ lamp\ and\ ballast = \frac{Average\ \ power\ of\ \ lighting\ circuit, W}{Number\ of\ \ lamps} \tag{6.3}$$

If the lighting circuits contain different types of lamps, power consumption for each type of lamp can be determined using spot measurement.

Lighting Power Density: Total power consumption of lamps and ballasts for each type of area could be determined by measuring the power of lighting circuits or multiplying the power consumption of each type of lamp including ballast and number of lamps of each type. Floor areas for different usages can be determined from floor plan layout drawings. Finally, the lighting power density should be calculated using Eq. (6.2) for different types of usage areas.

Lux Level: Lux level should be measured in a number of locations for each type of area using the lux meter to determine the range of and average lux level. An appropriate lux level range of the lux meter should be selected starting from the lowest lux level. The lux meter should be kept on the surface where the measurement is required or about 1 m from the floor (waist level). For each measurement, a minimum of 4 readings should be taken and the average of the readings should be computed. Generally, about 20 to 25 readings of lux levels are taken for each type of area to determine the range of and average value of lux level.

Data Arrangement: Lighting power density, lux level and benchmark data for each type of usage area can be tabulated as shown in Table 6.3.

Table 6.3: *Example of lux level, lighting power density and benchmarking data for different types of areas.*

Location	Types of lamps	Measured lux level, Lux	Benchmark lux level based on SS531, Lux	Measured lighting power density, W/m^2	Benchmark lighting power density based on SS530: 2014, W/m^2
Office areas	Linear fluorescent	400 – 550 (Average: 520)	500	14	12
Conference rooms	Linear fluorescent and CFL	530 – 700 (Average: 640)	500	17	16
Corridors	Linear fluorescent and CFL	130 – 220 (Average: 170)	150	12	7
Lift lobbies	Linear fluorescent and CFL	160 – 210 (Average: 160)	150	13	7
Departmental stores	CDM, Linear fluorescent and CFL	540 – 760 (Average: 670)	500	23	15 (+ 5)
Car parks	Linear fluorescent	60 – 95 (Average: 82)	75	5.5	3

6.6 Best Practices

i. If lux levels are higher than the benchmark values, lux levels should be reduced by (a) de-lamping, (b) using task lighting and (c) replacing existing lamps with appropriate types and spacing of lamps

ii. If lighting power densities are higher than the benchmark values, lighting power densities should be reduced by (a) proper lighting design, (b) use of higher efficacy lamps and (c) use of high efficiency ballasts
iii. Reflectors of high reflectivity should be used to improve the optical efficiency
iv. Timers should be used to switch on / off the lamps according to the occupancy schedules
v. Daylight sensors with suitable controllers should be used to automatically dim or switch off the lamps of perimeter zones when the level of daylight increases
vi. Occupancy sensors should be installed to switch off the lamps of toilets, meeting rooms, corridors, storage rooms, carparks etc. when the areas are not occupied
vii. Skylights, light shelves and light pipes should be used to transmit the natural daylight into the interior spaces of buildings and minimise the use of artificial lighting

6.7 Case Study

An energy audit recommended the replacement of T5 lamps of an industrial plant to energy efficient LED lamps. A total of 8,000 nos. of 4 feet T5 lamps, including ballast, of an industrial plant are subsequently retrofitted with an equal number of energy efficient LED lamps. The average power consumption of the 4 feet T5 lamps including ballast was measured at few selected lighting electrical circuit boards. Measured data showed that baseline average power consumption of each 4 feet T5 lamp including ballast was 32.4 W. Lux levels at different areas with the 4 feet T5 lamps were also measured. The lux levels generally complied with SS531.

The average power consumption of the newly installed LED lamps were measured at the same lighting electrical circuit boards. Measured data showed that post-implementation, the average power consumption for each new LED lamp was 22.7 W. Illuminance levels at same areas with the new LED lamps were also measured. Illuminance levels with the new LED lamps were generally slightly higher than the baseline illuminance levels. The calculation of energy and cost savings due to the retrofitting of the lamps is presented below:
Average measured power consumption for each 4 feet T5 lamp including ballast = 32.4 W

Average measured power consumption for each new 4 feet LED lamp = 22.7 W

Power savings per lamp = 32.4 - 22.7
= 9.7 W

Total number of lamps retrofitted in production area	= 6700 pieces
Operating hours for production area	= 24 hours/day
Annual operating hours for production area	= 24 hours/day x 365 days/year = 8,760 hours/year
Annual electrical energy savings	= 9.7 x 6700 x 8760 / 1000 = 569,312 kWh/year
Total number of lamps retrofitted in office area	= 8,000 - 6700 = 1,300 pieces
Operating hours for office area	= 14 hours/day
Annual operating hours for office area	= 14 hours/day x 260 days/year = 3,640 hours/year
Annual electrical energy savings	= 9.7 x 1300 x 3640 / 1000 = 45,900 kWh/year
Total annual electrical energy savings	= 569,312 + 45,900 = 615,212 kWh/year
Electricity tariff	= $0.20 / kWh
Annual energy cost savings	= 615,212 x 0.20 **= $123,042 / year**

7 Industrial Systems

7.1 Steam and Hot Water Systems

Steam and hot water are used in building and industrial processes such as laundries, kitchens, space heating, heating of industrial processes, separation of components, chemical reactions, mechanical drives etc. In chemical industries, pharmaceutical industries, paper industries, food manufacturing plants etc., a large percentage of the energy consumption is accounted for by the steam and hot water generation processes. Boilers and heat pumps are commonly used in buildings and industries for the generation of steam and hot water. Proper measurement systems to determine the actual operating performance and optimisation of the steam and hot water generation processes may contribute significant operating energy and cost savings.

Learning Outcomes

Participants will be able to:

i. Understand basic operation of the steam and hot water systems
ii. Identify suitable energy performance indicators
iii. Identify parameters to be measured to calculate the energy performance
iv. Select locations for measuring parameters
v. Calculate energy performance of steam and hot water systems
vi. Understand basic information about audit of steam and hot water systems

7.2 Boiler Systems

A boiler generally consists of a pressure vessel and combustion chamber. Solid, liquid or gaseous fuel is burnt in the combustion chamber to produce hot flue gases. Finally, heat is transferred from the hot flue gas to the water of the pressure vessel through tubular heat exchanger and steam or hot water is produced. Water boilers are generally operated at low-pressure and used primarily for producing hot water. Steam boilers, on the other hand, are generally operated at high-pressure and used for producing steam.

Boilers are broadly classified as: (a) Fire tube boilers and (b) Water tube boilers. For the fire tube boilers, flue gas flows through the tubes which are submerged in water. Heat is transferred from the flue gas to the water through the wall of the tubes. Saturated steam is generated and accumulated at the upper section of the boiler drum as shown in Figure 7.1. However, for water tube boilers, flue gas flows outside of the tubes which contain water. Heat

is transferred from the flue gas to the water through the wall to the tubes. Saturated steam is produced and accumulated at the upper section of the boiler drum as shown in Figure 7.2.

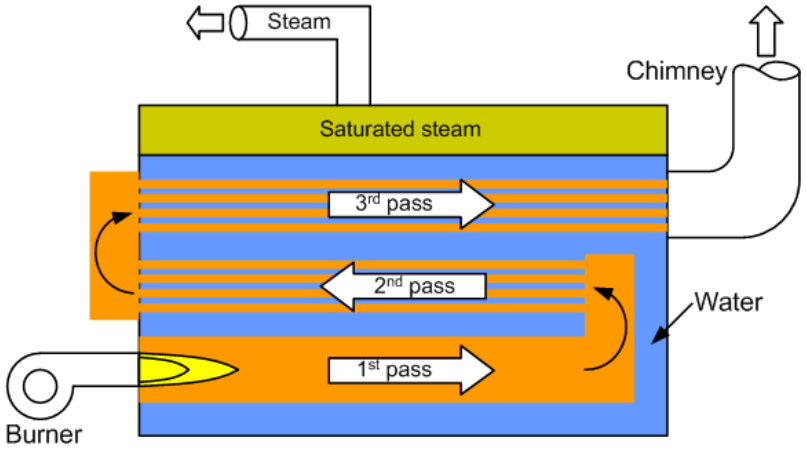


Figure 7.1: *Fire tube boiler.*

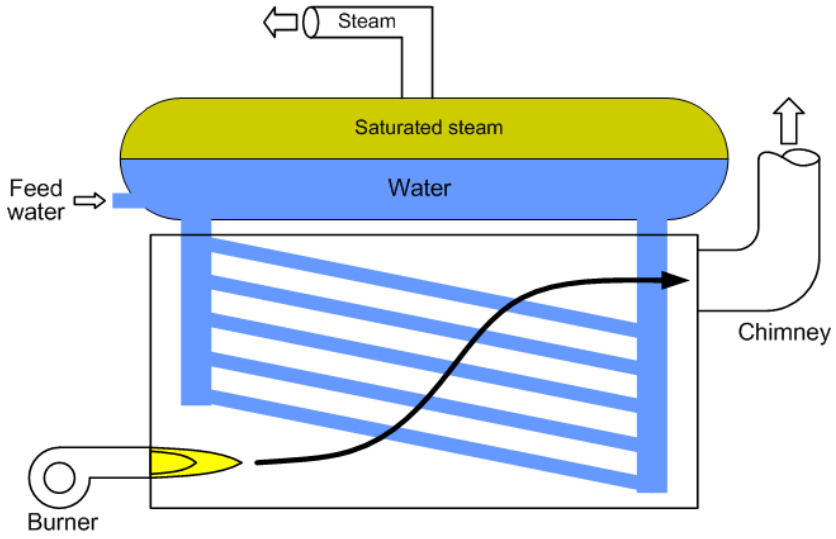


Figure 7.2: *Water tube boiler.*

7.2.1 Boiler Basic Operations

The basic operation of a boiler system is shown schematically in Figure 7.3. Feed water is treated in a chemical treatment plant to prevent scaling of the boiler's tubes. Feed water is then heated in the deaerator using steam or returned hot condensate to vent out the dissolved air in the feed water. Finally, the feed water is supplied to the boiler using feed water pump. The feed water contains some degree of suspended and dissolved solids which accumulate

inside the boiler as the boiler operation continues. Increasing concentration of dissolved solids may lead to carryover of the dissolved solids into the steam leading to the damage of piping, steam traps and even process equipment. Increasing concentration of suspended solids, on the other hand, can form sludge which hinders the heat transfer rate and boiler efficiency. To overcome these problems, bottom and surface blowdowns are used. Bottom blowdown is intermittent and is used primarily to remove the suspended solids. Dissolved solids are removed using surface blowdown which is continuous. Solid content of boiler water is generally measured using conductivity probes and the rates of the blowdowns are controlled to maintain the solid content in the boiler water below the recommended values.

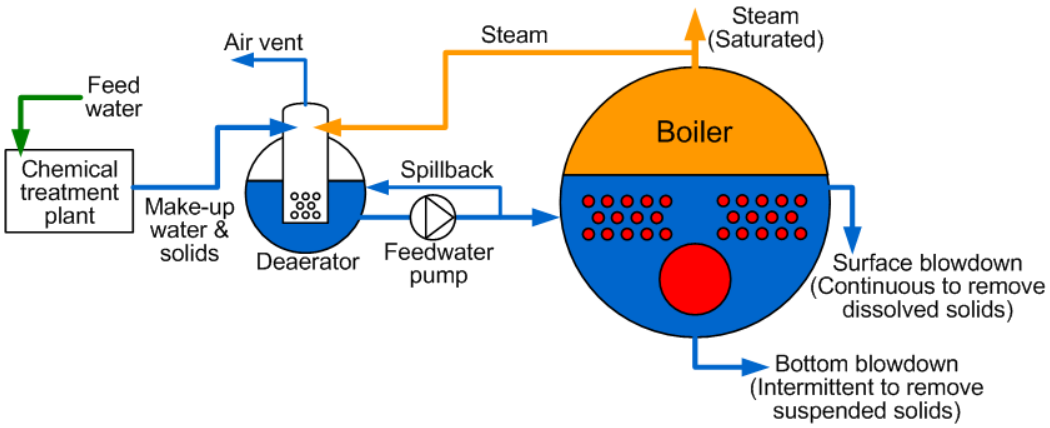


Figure 7.3: *Basic operation of boiler systems.*

7.2.2 Boiler Draught

The quantity of air required for complete combustion of different types of fuel can be computed theoretically. However, in practice, based on the type of fuel and burner used in the boilers, a certain percentage of excess air (usually about 10% to 15%) is supplied for proper mixing of the air and fuel to ensure complete combustion. Too much excess air would result in unnecessary heat loss through flue gas discharge. Boiler draught systems are designed to provide adequate air for combustion and flue gas discharge to the atmosphere through the chimney.

7.2.3 Enthalpy of Water and Steam

Energy content per unit mass of water or steam is called enthalpy. As water is heated in the boiler systems, temperature and enthalpy of the water gradually increase as shown in Figure 7.4. Suppose, the pressure of a boiler is 1 atm (1.013 bar) and the temperature of the feed water is 30^{o}C. Boiling temperature of water at 1 atm pressure is 100^{o}C. Due to the heating, the temperature of the feed water will increase from 30^{o}C to the boiling temperature of 100^{o}C without any change of phase. This heating process is known as sensible heating. Once the temperature of the water reaches the boiling temperature, the water is called saturated water. After reaching the boiling temperature, water absorbs heat at constant boiling temperature and changes its phase from saturated water to saturated steam. This heating process is known as boiling (latent heat transfer) and the generated steam at saturation temperature is called saturated steam. If the generated steam is further heated to a higher temperature (say at 250^{o}C as shown in Figure 7.4), this heating process is called sensible heating and the steam of temperature higher than the saturation temperature is known as superheated steam. The enthalpies of water, saturated steam and superheated steam at different temperatures and pressures can be obtained from steam tables. The enthalpies of water and steam at the different stages mentioned above are shown in Figure 7.4.

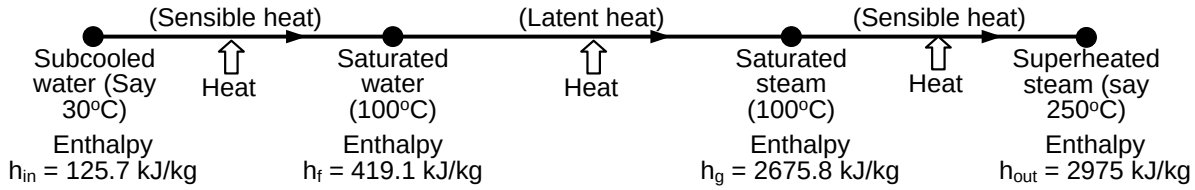


Figure 7.4: *Generation of steam at 1 atm (1.013 bar) pressure.*

Generally, the pressure of the boiler is higher than 1 atm. Steam generation process for a boiler of 5 bar pressure is illustrated in Figure 7.5. Boiling temperature of water at 5 bar pressure increases to 151.8^{o}C (Figure 7.5) compared to 100^{o}C at 1 atm pressure shown in Figure 7.4.

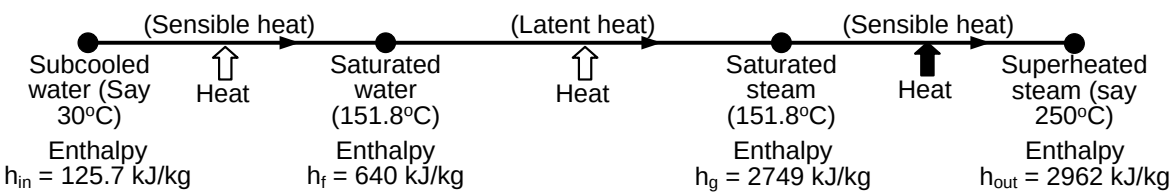


Figure 7.5: *Generation of steam at 5 bar pressure.*

At pressure of 5 bar, Figure 7.5 shows:

Sensible heat transfer to water = $h_f - h_{in}$ = 640 – 125.7 = 514.3 kJ/kg

Latent heat transfer to generate steam $h_{fg} = h_g - h_f$ = 2749 – 640 = 2109 kJ/kg

Sensible heat transfer to superheated steam = $h_{out} - h_g$ = 2962 – 2749 = 213 kJ/kg

where,

h_{in} = enthalpy of inlet subcooled water, kJ/kg

h_f = enthalpy of saturated water, kJ/kg

h_g = enthalpy of saturated steam, kJ/kg

h_{fg} = latent heat of vaporization, kJ/kg

h_{out} = enthalpy of outlet superheated steam, kJ/kg

Steam generation processes and changes of enthalpies are further elaborated in temperature vs. enthalpy diagram shown in Figure 7.6.

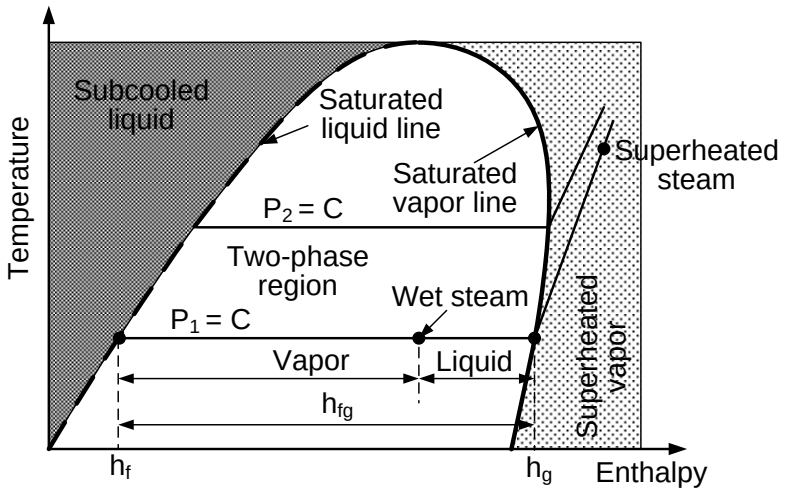


Figure 7.6: *Temperature vs. enthalpy diagram for steam generation processes.*

Wet steam contains mist of liquid water droplets and its properties are determined from the two-phase region of the temperature vs. enthalpy diagram. Dryness fraction of wet steam is defined as:

$$x = \frac{m_g}{m_g + m_f} \tag{7.1}$$

$$x = \frac{m_g}{m} \tag{7.2}$$

where,

x = dryness fraction of wet steam, dimensionless

m_g = mass of dry steam, kg

m_f = mass of mist of liquid water droplets, kg

m = mass of wet steam, kg

Enthalpy of wet steam at a pressure P can be calculated as:

$$h_{wet} = h_f + xh_{fg} \tag{7.3}$$

where,

h_{wet} = enthalpy of wet water at P, kJ/kg

h_f = enthalpy of saturated water at T_{sat}, kJ/kg

h_{fg} = latent heat of vaporisation at P, kJ/kg

P = pressure of steam, bar

T_{sat} = saturation temperature corresponding to steam pressure P, ^oC

x = dryness fraction of wet steam, dimensionless

Dryness fraction of dry saturated steam is unity. Therefore, the enthalpy of saturated steam at pressure P can be calculated using Eq. (7.3) as:

$$h_g = h_f + h_{fg} \tag{7.4}$$

where,

h_g = enthalpy of saturated steam at P, kJ/kg

h_f = enthalpy of saturated water at T_{sat}, kJ/kg

h_{fg} = latent heat of vaporisation at P, kJ/kg

P = pressure of steam, bar

T_{sat} = saturation temperature corresponding to steam pressure P, ^oC

If the temperature of steam is higher than the saturation temperature corresponding to the steam pressure, the condition of the steam is superheated. For instance, the pressure of the steam generation process shown in Figure 7.5 is 5 bar. The saturation temperature of steam corresponding to the steam pressure of 5 bar is 151.8^{o}C. If the temperature of steam of 5 bar pressure is higher than 151.8^{o}C, the condition of the steam will be superheated. The enthalpy of superheated steam can be determined using steam table corresponding to the pressure and temperature of the steam. The enthalpy of the superheated steam can also be calculated as:

$$h_{\sup} = h_f + h_{fg} + C_p\left(T_{\sup} - T_{sat}\right) \tag{7.5}$$

where,

h_{sup} = enthalpy of superheated steam at P and T_{sat}, kJ/kg

h_f = enthalpy of saturated water at T_{sat}, kJ/kg

h_{fg} = latent heat of vaporisation at P, kJ/kg

P = pressure of steam, bar

T_{sat} = saturation temperature corresponding to steam pressure P, ^oC

T_{sup} = temperature of superheated steam, ^oC

C_p = specific heat of superheated steam, kJ/kg K

(T_{sup} - T_{sat}) = degree of superheat, ^oC

The difference of the superheated and saturated steam temperatures (T_{sup} - T_{sat}) is known as degree of superheat. Specific heat of steam changes significantly with the change of temperature and pressure of superheated steam. Hence, enthalpy of superheated steam is generally determined using steam tables.

Steam is generated in the boiler as saturated steam and accumulated in the boiler drum. The saturated steam is heated in the superheater to generate superheated steam. An example of the forced circulation water tube boiler and superheater commonly used in the combined heat and power (CHP) plants is shown in Figure 7.7.

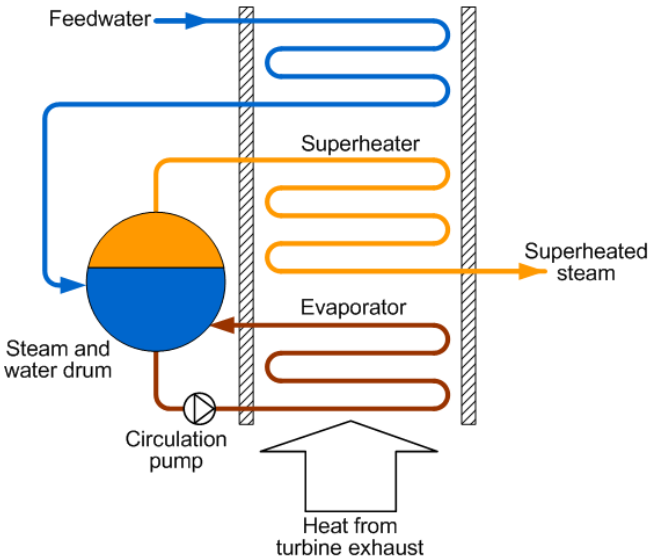


Figure 7.7: *Forced circulation water tube boiler and superheater.*

7.2.4 Energy Balance and Measurement of Boiler Efficiency

A typical energy flow diagram of a boiler system is shown in Figure 7.8. About 65% to 80% of the input fuel energy is used to generate steam of high temperature and pressure. A major part of the remaining fuel energy is discharged to the atmosphere as exhaust flue gas.

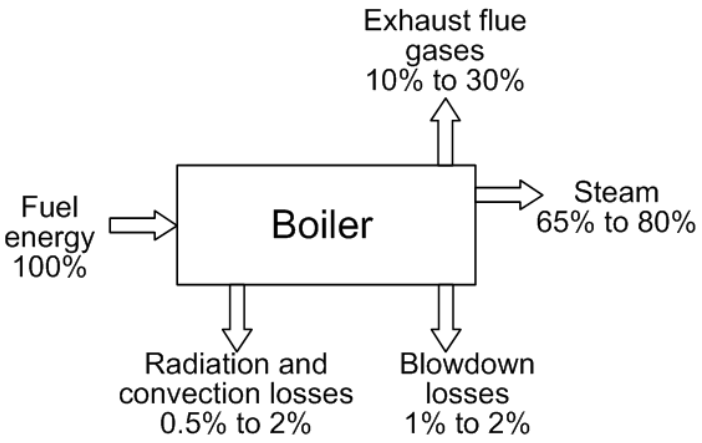


Figure 7.8: *Typical energy flow diagram of boiler system.*

To evaluate the energy performance of the boiler systems and identify the energy saving or optimisation opportunities, necessary parameters are measured at different locations of the boiler systems. One of the key energy performance indicators of the boiler system is thermal efficiency, which is commonly defined by neglecting the blow down effect as:

$$\eta_{boiler} = \frac{Energy\ \ output\ \ of\ \ steam}{Energy\ \ input\ \ of\ \ \ fuel} \tag{7.6}$$

$$\eta_{boiler} = \frac{V_s \rho_s h_s - V_{fw} \rho_{fw} h_{fw}}{V_{fuel} \rho_{fuel} GCV} \tag{7.7}$$

where,

η_{boiler} = efficiency of boiler, dimensionless

V_s = steam generation rate, m^3/s

ρ_s = density of steam at boiler outlet temperature T_s and pressure P_s, kg/m^3

h_s = enthalpy of steam at boiler outlet temperature T_s and pressure P_s, kJ/kg

V_{fw} = volume flow rate of feed water, m^3/s

ρ_{fw} = density of feed water at temperature T_{fw}, kg/m^3

h_{fw} = enthalpy of water at feed water temperature T_{fw}, kJ/kg

V_{fuel} = fuel consumption rate, m^3/s

ρ_{fuel} = density of fuel, kg/m^3

GCV = gross calorific value of fuel, kJ/kg of fuel

Flow rates, temperatures and pressures of steam, feed water and fuel can be measured at point-1, 2 and 3 respectively as shown in Figure 7.9.The measurement instruments that are typically used to measure these parameters can be found in Table 7.1.

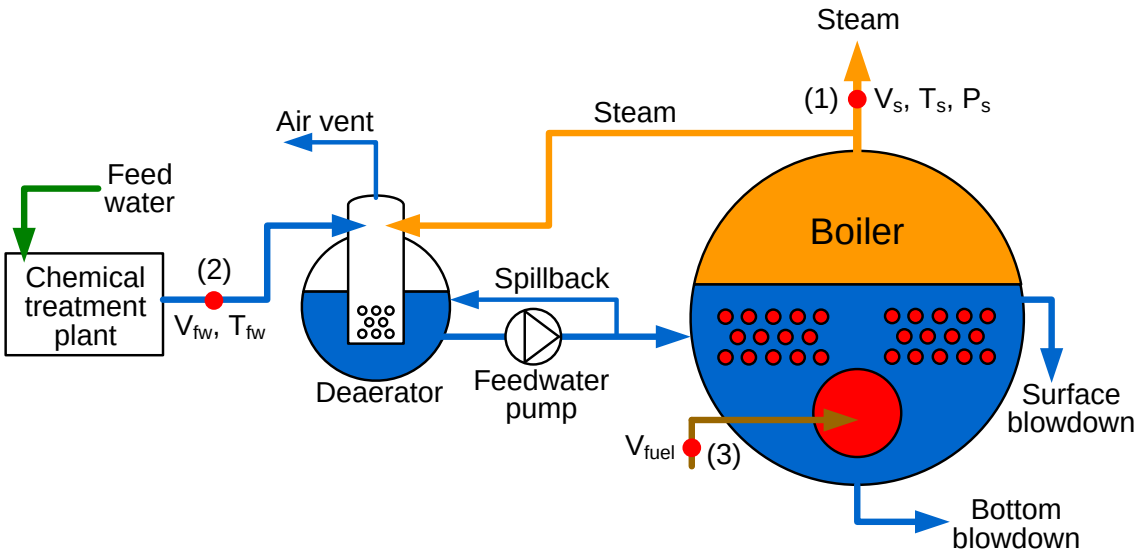


Figure 7.9: *Typical measurement locations for calculating the efficiency of boiler.*

7.2.5 Calculation of Blowdown Rate

Conductivity probes are commonly used in boiler systems to measure the solid content of water inside the boiler vessel and control the blowdown rate. As the bottom blowdown is intermittent and the flow rate of surface blowdown is relatively small, mass balance of boiler systems is carried out (other than measuring using flowmeters) to determine the blowdown rate as:

$$Mass\ flow\ rate\ of\ incoming\ streams = Mass\ flow\ rate\ of\ outgoing\ streams \qquad (7.8)$$

Mass balance of water and steam for the boiler systems shown in Figure 7.9 gives:

$$V_{fw}\rho_{fw} = V_s\rho_s + (V_{sb} + V_{bb})\rho_{bw}$$

$$V_{tb} = (V_{sb} + V_{bb}) = \frac{V_{fw}\rho_{fw} - V_s\rho_s}{\rho_{bw}} \qquad (7.9)$$

where,

V_{tb} = total blowdown rate of boiler, m^3/s

V_{sb} = Surface blowdown rate of boiler, m^3/s

V_{bb} = Bottom blowdown rate of boiler, m^3/s

ρ_{bw} = density of blowdown water at saturation temperature corresponding to the pressure of boiler, kg/m^3

V_{fw} = volume flow rate of feed water, m^3/s

ρ_{fw} = density of feed water at temperature T_{fw}, kg/m^3

V_s = steam generation rate, m^3/s

ρ_s = density of steam at boiler outlet temperature T_s and pressure P_s, kg/m^3

Energy losses through the blowdown water can be calculated as:

$$Q_{tb} = V_{tb}\rho_{bw}h_{f,bd} \tag{7.11}$$

where,

Q_{tb} = total energy losses through the blow down water, kW

$h_{f,bd}$ = enthalpy of blowdown water at saturation temperature corresponding to the pressure of boiler, kJ/kg

7.2.6 Measurement of Recoverable Energy from Blowdown

Suspended solid content of bottom blowdown is generally quiet high. Hence, energy is not recovered from the bottom blowdown. Significant amount energy can be recovered from the surface blowdown. As the blowdown water is saturated at boiler pressure (higher than ambient), flash steam is generated once the pressure of the blowdown water is reduced to the atmospheric pressure in the flash vessel. Flash steam can be recovered for low pressure applications or transferred to the feed water tank for the recovery of heat and condensate. Blowdown water can be further used to pre-heat the make-up water of boiler as shown in Figure 7.10.

The temperature of surface blowdown water at point-1 is the saturation temperature of water corresponding to the pressure of boiler. After flashing of steam in the flash vessel, the temperature of water at point-2 will be the boiling temperature at 1 atm pressure, which is 100°C. A flow meter can be installed after the flash vessel at point-2 to measure the flow rate of water. The flash steam generation rate (at point-3) can be calculated using the mass and energy balance for the flash vessel. Mass balance for the flash vessel gives:

$$m_{sb,1} = m_{w,2} + m_{fs,3} \tag{7.12}$$

$$V_{sb,1}\rho_{bw,1} = V_{w,2}\rho_{w,2} + V_{fs,3}\rho_{fs,3} \tag{7.13}$$

Energy balance for the flash vessel gives:

$$V_{sb,1}\rho_{bw,1}h_{sb,1} = V_{w,2}\rho_{w,2}h_{w,2} + V_{fs,3}\rho_{fs,3}h_{fs,3} \tag{7.14}$$

Combining Eqs. (7.13) and (7.14) gives:

$$V_{w,2}\rho_{w,2}h_{sb,1} + V_{fs,3}\rho_{fs,3}h_{sb,1} = V_{w,2}\rho_{w,2}h_{w,2} + V_{fs,3}\rho_{fs,3}h_{fs,3}$$

$$m_{fs,3} = V_{fs,3}\rho_{fs,3} = \frac{V_{w,2}\rho_{w,2}\left(h_{sb,1} - h_{w,2}\right)}{h_{fs,3} - h_{sb,1}} \tag{7.15}$$

where,

$m_{sb,1}$ = mass flow rate of surface blowdown at point-1, kg/s

$m_{w,2}$ = mass flow rate of water at point-2, kg/s

$m_{fs,3}$ = mass flow rate of flash steam at point-3, kg/s

$V_{sb,1}$ = volume flow rate of surface blowdown at point-1, m^3/s

$V_{w,2}$ = volume flow rate of water at point-2, m^3/s

$V_{fs,3}$ = volume flow rate of flash steam at point-3, m^3/s

$\rho_{sb,1}$ = density of surface blowdown water (at point-1) at saturation temperature corresponding to the pressure of boiler, kg/m^3

$\rho_{w,2}$ = density of saturated water (at point-2) at 100°C, kg/m^3

$\rho_{fs,3}$ = density of saturated flash steam (at point-3) at 100°C, kg/m^3

$h_{sb,1}$ = enthalpy of surface blowdown water (at point-1) at saturation temperature corresponding to the pressure of boiler, kJ/kg

$h_{w,2}$ = enthalpy of saturated water (at point-2) at 100°C, kJ/kg

$h_{fs,2}$ = enthalpy of saturated flash steam (at point-3) at 100°C, kJ/kg

Energy recovery rate with the flash steam at point-3 ($Q_{fs,3}$) is:

$$Q_{fs,3} = m_{fs,3}h_{fs,3} \tag{7.16}$$

Energy recovery rate by the make-up water from the heat exchanger shown in Figure 7.10 can be calculated by measuring the temperature at point-4 as:

$$Energy\ recovery\ rate\ by\ cold\ \ stream = Energy\ rejection\ rate\ by\ hot\ stream \tag{7.17}$$

$$Energy\ recovery\ rate\ by\ the\ make\text{-}up\ water = V_{w,2}\rho_{w,2}\left(h_{w,2} - h_{w,4}\right) \tag{7.18}$$

where,

$h_{w,4}$ = enthalpy of water at temperature of point-4, kJ/kg

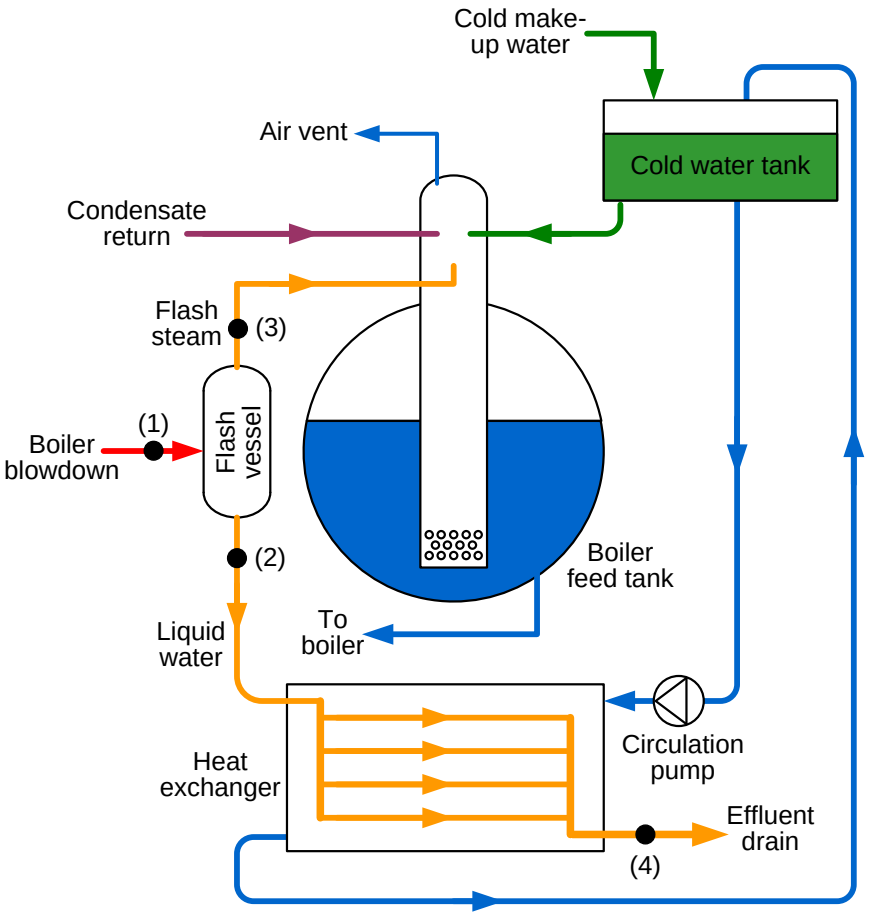


Figure 7.10: *Blowdown energy recovery and measurement systems.*

7.2.7 Measurement of Power of Auxiliary Equipment

Auxiliary equipment of a typical boiler system is shown in Figure 7.11. Make-up water pumps, condensate recovery pumps, feed water pumps, blower of burner and draft fans are the main auxiliary equipment. Power meters are used to measure the power consumption of the auxiliary equipment. Proper designing of the piping layout, removing of unnecessary flow modulating or balancing valves and regulating the speed of the pumps and blowers using smart control strategies based on real-time instantaneous demand of steam may contribute significantly in energy savings of the auxiliary equipment.

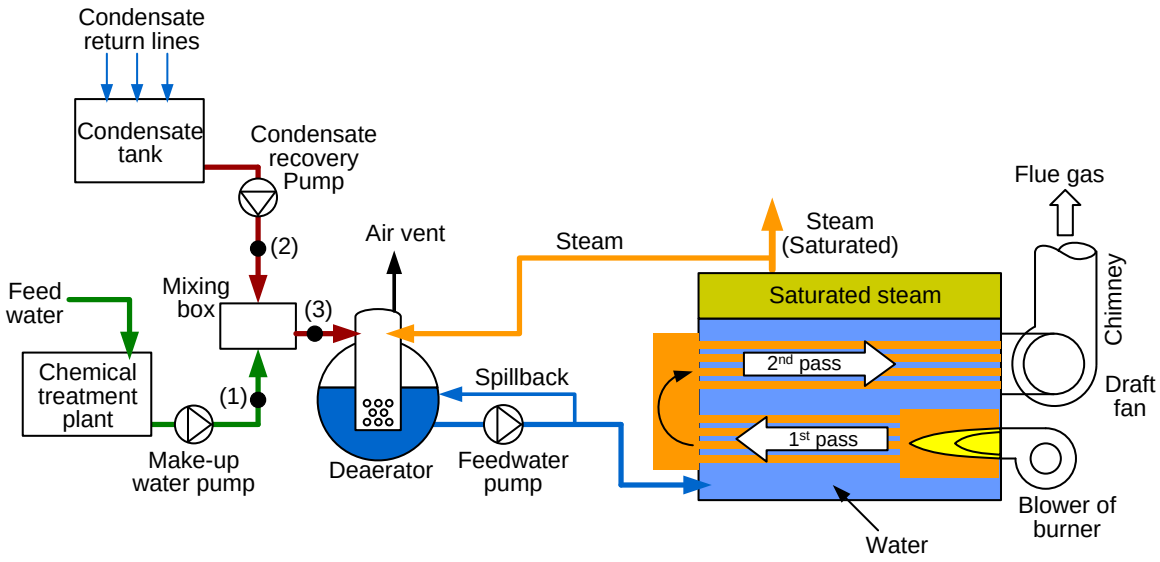


Figure 7.11: *Auxiliary equipment of typical boiler system.*

7.2.8 Measurement of Condensate Recovery Rate

Steam is mainly used in industrial plants for the heating of different processes by extracting its latent heat. The resulting condensate could be at steam temperature and still contain a considerable amount of heat energy. The recovery of condensate results in: (a) lower fuel cost, (b) lower water cost, (c) lower water treatment cost and (d) less blowdown. A water flow meter could be installed at point-2 of Figure 7.11 to measure the condensate recovery rate. In practice, a water flow meter is usually installed at point-1 (Figure 7.11) to measure the make-up water flow rate. Installation of a water flow meter at point-2 could be avoided by measuring the temperatures at point-1, 2 and 3 and carrying out the energy balance across the mixing box as:

$$Inlet\ energy\ to\ mixing\ box = Outlet\ energy\ \ from\ mixing\ box \tag{7.19}$$

$$V_{mw,1}\rho_{mw,1}h_{mw,1} + V_{cw,2}\rho_{cw,2}h_{cw,2} = V_{w,3}\rho_{w,3}h_{w,3}$$

$$V_{mw,1}\rho_{mw,1}h_{mw,1} + V_{cw,2}\rho_{cw,2}h_{cw,2} = \left(V_{mw,1}\rho_{mw,1} + V_{cw,2}\rho_{cw,2}\right)h_{w,3}$$

$$m_{cw,2} = V_{cw,2}\rho_{cw,2} = \frac{V_{mw,1}\rho_{mw,1}\left(h_{w,3} - h_{mw,1}\right)}{h_{cw,2} - h_{w,3}} \tag{7.20}$$

where,

$m_{CDW,2}$ = mass flow rate of condensate at point-2, kg/s

$V_{mw,1}$ = volume flow rate of make-up water at point-1, m^3/s

$V_{CDW,2}$ = volume flow rate of condensate at point-2, m^3/s

$V_{w,3}$ = volume flow rate of mixed water at point-3, m^3/s

$\rho_{mw,1}$ = density of make-up water at temperature T_1, kg/m^3

$\rho_{CDW,2}$ = density of condensate at temperature T_2, kg/m^3

$\rho_{w,3}$ = density of mixed water at temperature T_3, kg/m^3

$h_{mw,1}$ = enthalpy of make-up water at temperature T_1, kJ/kg

$h_{CDW,2}$ = enthalpy of condensate at temperature T_2, kJ/kg

$h_{w,3}$ = enthalpy of mixed water at temperature T_3, kJ/kg

T_1 = temperature of make-up water at point-1, ^oC

T_2 = temperature of condensate at point-2, ^oC

T_3 = temperature of mixed water at point-3, ^oC

7.2.9 Measurement of Radiation and Convection Losses

As the drum of the boiler and steam piping systems are insulated, radiation and convection losses from the boiler systems are relatively small (typically about 0.5% to 2% of the input fuel energy). However, the percentage of the radiation and convection losses will be increased remarkably if the boiler systems are not carefully insulated or the boilers are operated at low load.

Convection heat loss can be calculated as:

$$Q_{conv} = hA\left(T_{surface} - T_{air}\right) \tag{7.21}$$

where,

Q_{conv} = convection heat loss, kW

h = convective heat transfer coefficient of air, $kW/(m^2\ K)$

A = area of exposed surfaces of boiler drum and steam pipes, m^2, m^3/s

$T_{surface}$ = temperature of exposed surfaces of boiler drum and steam pipes, ^oC

T_{air} = temperature of surrounding air, ^oC

Convective heat transfer coefficient *(h)* of air depends on the temperature of surrounding air, flow geometry and velocity of air. The temperature of the exposed surfaces of boiler drum and steam pipes can be measured using infrared temperature sensors.

Radiation heat loss can be calculated as:

$$Q_{rad} = \sigma A \varepsilon \left(T_{surface}^4 - T_{air}^4 \right) \tag{7.22}$$

where,

Q_{rad} = radiation heat loss, kW

σ = Stefan-Boltzmann constant, 5.67×10^{-5} kW/m^2 K^4

ε = emissivity of surface, dimensionless

A = area of exposed surfaces of boiler drum and steam pipes, m^2, m^3/s

$T_{surface}$ = temperature of exposed surfaces of boiler drum and steam pipes, K

T_{air} = temperature of surrounding air, K

7.2.10 Measurement of Excess Air for Combustion

Depending on the type of fuel and the design of the burner systems of the boiler, a certain percentage of excess air is supplied to the combustion chamber for proper atomisation, mixing and combustion of the fuel. Insufficient air will lead to incomplete combustion of the fuel resulting in (a) wastage of fuel, (b) build-up of soot and (c) explosion due to the accumulation unburned fuel in the surrounding air. Too much excess air, on the other hand, will result in unnecessary heat loss through flue gas discharge. The percentage of the excess air can conveniently be measured at the chimney of the boilers using gas analysers which can measure the percentage of excess air, the content of O_2, CO_2, CO etc. in the flue gas.

7.2.11 Measurement of Recoverable Energy from Flue Gas

The temperature of the flue gas leaving the combustion chamber of the boiler typically ranges from 150^{o}C to 200^{o}C, which contains about 10% to 20% of the input fuel energy. Heat energy of the flue gas can be recovered using heat exchangers (known as economizers) to pre-heat the feed water or the combustion air as shown in Figure 7.12 to improve the overall efficiency of boiler. The amount of recoverable heat depends on the cold fluid (feed water or combustion air) temperature, flue gas temperature and the acid dew point of the flue gas.

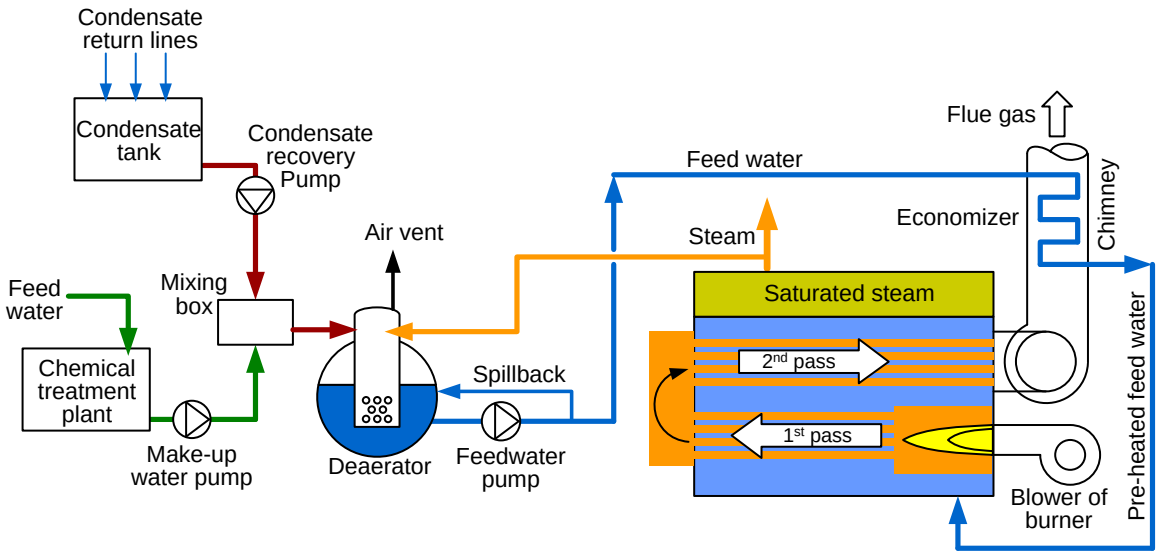


Figure 7.12: *Energy recovery from flue gas using economizer.*

Recoverable Energy: The amount of recoverable heat energy from the flue gas can be determined as follows:

Suppose, measured present temperature of flue gas in the chimney= $T_{p,fg}$ ^oC

Allowable flue gas temperature (based on sulphur content fuel and corresponding acid dew point) = $T_{a,fg}$ ^oC

Possible reduction in temperature of the flue gas = $(T_{p,fg} - T_{a,fg})$ ^oC

Fuel consumption rate = V_{fuel} m^3/s

Density of fuel = ρ_{fuel} kg/m^3

Mass flow rate of fuel = $V_{fuel} \times \rho_{fuel}$ kg/s

Present air-to-fuel ratio = n:1

Air flow rate to the combustion chamber = $(n \times V_{fuel} \times \rho_{fuel})$ kg/s

Total mass flow rate of flue gas = Fuel flow rate + air flow rate

$= (V_{fuel} \times \rho_{fuel} + n \times V_{fuel} \times \rho_{fuel})$

$= (n+1) \times V_{fuel} \times \rho_{fuel}$ kg/s

Specific heat capacity of flue gas = $C_{p,g}$ kJ/kg.K

Possible heat recovery rate = Mass flow rate of flue gas x Specific heat capacity x Temperature reduction of flue gas

$= (n+1) \times V_{fuel} \times \rho_{fuel} \times C_{p,g} \times (T_{p,fg} - T_{a,fg})$ kW

Feed Water Outlet Temperature: Feed water outlet temperature can be determined as:

Suppose, volume flow rate of feed water at the inlet of economizer = V_w m^3/s

Density of feed water at the inlet of economizer = ρ_w kg/m^3

Specific heat capacity of feed water = $C_{p,w}$ kJ/kg.K

Temperature of feed water at the inlet of economizer = $T_{w,in}$ ^oC

Temperature of feed water at the outlet of the economizer ($T_{w,out}$) can be determined using energy balance for the economizer as:

$$Energy\ recovered\ by\ \ feed\ water = Energy\ rejected\ by\ \ flue\ gas \tag{7.23}$$

$$V_w \rho_w C_{p,w} \left(T_{w,out} - T_{w,in}\right) = (n+1) V_{fuel} \rho_{fuel} C_{p,g} \left(T_{p,\,fg} - T_{a,\,fg}\right)$$

$$T_{w,out} = T_{w,in} + \frac{(n+1) V_{fuel} \rho_{fuel} C_{p,g} \left(T_{p,\,fg} - T_{a,\,fg}\right)}{V_w \rho_w C_{p,w}} \tag{7.24}$$

7.2.12 Measuring Sensors for Boiler Systems

Commonly used sensors for measuring different parameters of boiler systems are presented in Table 7.1.

Table 7.1: *Commonly used sensors for measuring different parameters of boiler systems*

Sensor type	Parameters	Recommended accuracy
RTD / Thermocouples	Temperature of feed water, steam and flue gas	± 0.1 to ± 0.5^{o}C
Infrared sensor	Boiler surface temperature	± 1^{o}C
Ultrasonic / full bore magnetic flowmeter	Volume or mass flow rate of feed water and condensate	± 2%
Vortex, Orifice plate, Turbine and Pitot tube flowmeters	Volume or mass flow rate of steam	
Power meters	Pumps and blower power consumption	± 1%.
Pressure gauge / Pressure transducer	Steam pressure	±0.5%

7.2.13 Accuracy of Sensors

Accuracy of sensors is usually expressed as (a) percentage of measured value or actual reading and (b) percentage of full scale deflection.

Percentage of measured value or actual reading: For example, the uncertainty of a flow meter is given as ± 2% of the actual value. If the actual flow rate is 1000 kg/hr, the flow meter will indicate between:
(1000 – 2% of 1000) kg/hr = 980 kg/hr
And
(1000 + 2% of 1000) kg/hr = 1020 kg/hr.

Similarly, if the actual flow rate is 500 kg/hr, the error is still ± 2% of the actual value and the flow meter will indicate between:
(500 – 2% of 500) kg/hr = 490 kg/hr
And
(500 + 2% of 500) kg/hr = 510 kg/hr

Percentage of full scale deflection (FSD): For example, the uncertainty of the flow meter is given as ± 2% of FSD. This means that the measurement error is expressed as a percentage of the maximum flow that the flowmeter can handle. If the flow meter can handle a maximum flow rate of 1000 kg/hr, the uncertainty of actual flow is ± 2% of 1000 kg/hr, or ±20 kg/hr. If the actual flow rate is 1000 kg/hr, the flow meter will indicate between:

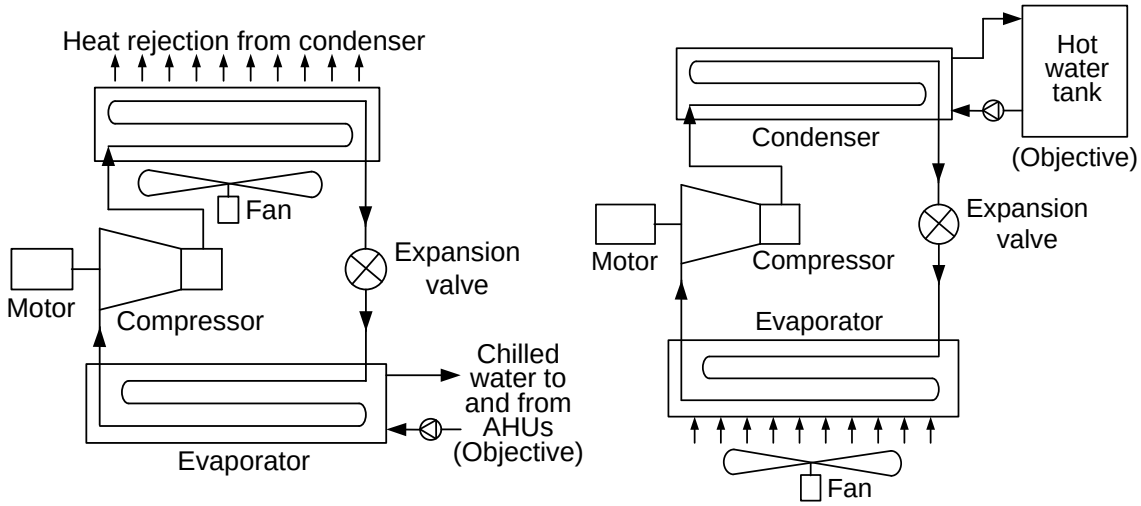
(1000 – 20) kg/hr = 980 kg/hr
And
(1000 + 20) kg/hr = 1020 kg/hr.

Now, if the actual flow rate is 500 kg/hr, the error is still ± 20 kg/hr and the flow meter will indicate between:
500 – 20 = 480 kg/hr
And
500 + 20 = 520 kg/hr.

7.3 Heat Pump Systems

Air conditioning machines and heat pumps operate on the same cycle but differ in their objectives as shown in Figure 7.13. The objectives of the air conditioning machines are to maintain the spaces at a low temperature and relative humidity by removing heat from the spaces and condensing the moisture of the circulating air. Discharging the heat of the air conditioning spaces to the ambient air at higher-temperature is a necessary part of the operation of air conditioning machines, not the purpose.

The objective of the heat pumps, on the other hand, is to heat up a medium or space. Heat pumps absorb heat from a relatively low temperature medium, such as ambient air or low temperature waste heat, and supply this heat to the high-temperature medium or space. Cooling the ambient air by absorbing the heat is a necessary part of the operation of heat pumps, not the purpose.



(a) Air conditioning machine (b) Heat pump

Figure 7.13: *Operating cycles and objectives of air conditioning machines and heat pumps.*

Pressure vs. specific enthalpy diagram for air conditioning machines (A/C) and heat pumps (HP) is shown in Figure 7.14. The temperatures of refrigerant in the condenser and evaporator are proportional to their pressures. Required compressor lift (pressure difference between condenser and evaporator) for the heat pumps is generally higher than the air conditioners. Power consumption of compressors increases with the increase of compressor lift. Heat pumps are used for relatively low temperature (typically between 50 to 90^{o}C) heating applications, such as hot water for hotel guest rooms, kitchen and industrial processes.

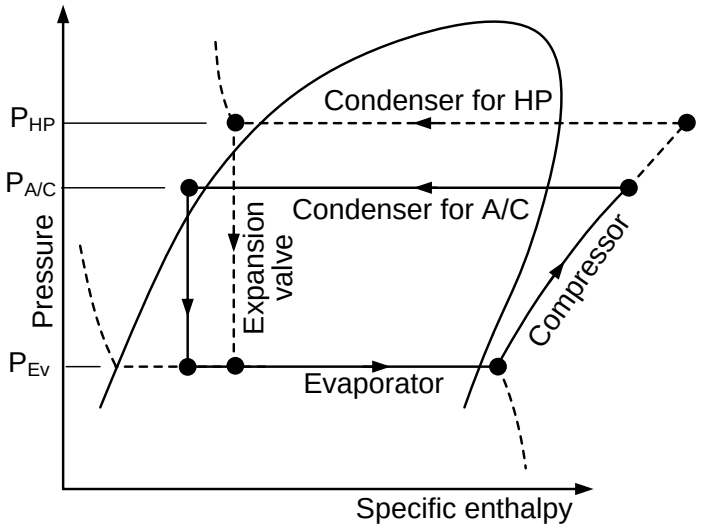


Figure 7.14: *Pressure vs. specific enthalpy diagram for air conditioning (A/C) machines and heat pumps (HP).*

7.3.1 Measurement of Heat Pump Performance

Same as the air conditioning machines, the performance of the heat pumps is expressed in Coefficient of Performance (COP). For the air conditioning machines or heat pumps, COP is defined as the ratio of the desired cooling or heating effect to the electrical power input to the motor of the compressor.

If the refrigeration cycle shown in Figure 7.15 functions as an air conditioning machine, the COP for the air conditioning is:

$$COP_{A/C} = \frac{Desired\ cooling\ effect\ in\ evaporator, Q_{eva}\ (kW)}{Input\ \ power\ to\ motor\ of\ \ compressor, W_{input}\ (kW)} \tag{7.25}$$

If the same refrigeration cycle functions as a heat pump, the COP for the heat pump is:

$$COP_{HP} = \frac{Desired\ heating\ effect\ in\ condener, Q_{cond}\ (kW)}{Input\ \ power\ to\ motor\ of\ \ compressor, W_{input}\ (kW)} \tag{7.26}$$

For the hermetic compressor, energy balance of the refrigeration cycle gives:

$$Q_{cond} = Q_{eva} + W_{input} \tag{7.27}$$

where,

Q_{cond} = heat rejection rate of condenser, kW

Q_{eva} = heat absorption rate of evaporator, kW

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

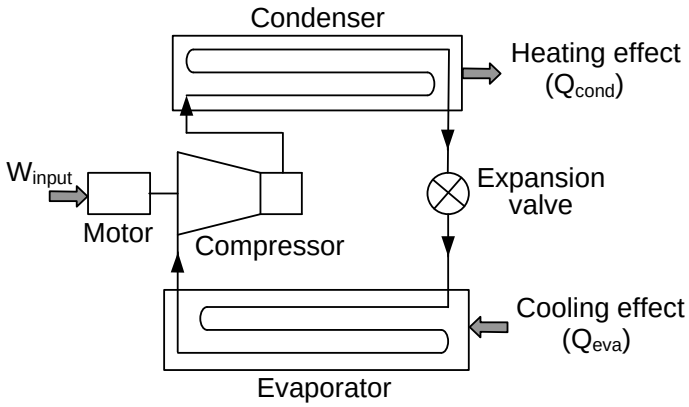


Figure 7.15: *Refrigeration cycle.*

Combining Eqs. (7.26) and (7.27) gives:

$$COP_{HP} = \frac{Q_{eva} + W_{input}}{W_{input}}$$

$$COP_{HP} = \frac{Q_{eva}}{W_{input}} + 1$$

$$COP_{HP} = COP_{A/C} + 1 \tag{7.28}$$

Flowmeter and temperature sensors are installed in hot water loop of condenser as shown in Figure 7.16 to measure the heating effect of the heat pumps:

$$Q_{cond} = V\rho_w C_p (T_2 - T_1) \tag{7.29}$$

where,

Q_{cond} = heating effect of heat pump, kW

V = volume flow rate of hot water, m^3/s

ρ_w = density of hot water, kg/m^3

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

T_1 = hot water inlet temperature to heat pump, ^oC

T_2 = hot water outlet temperature from heat pump, ^oC

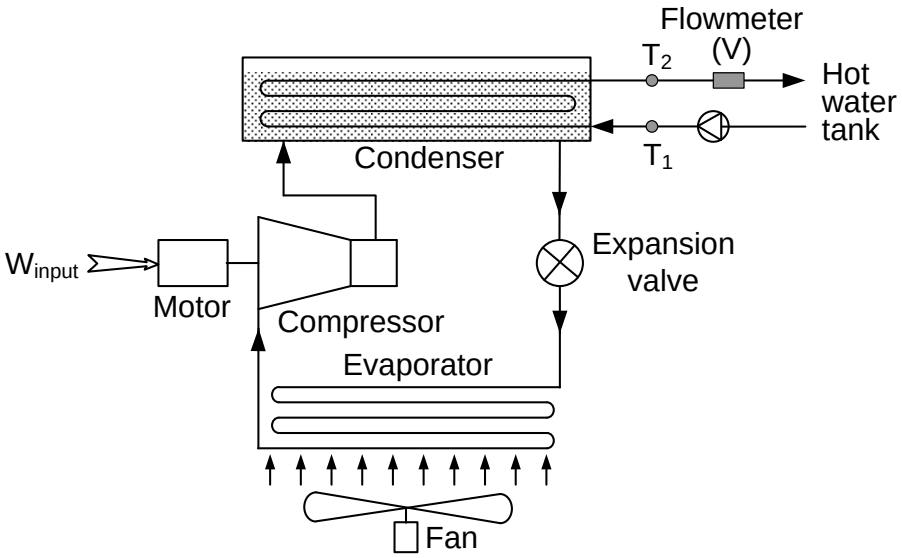


Figure 7.16: *Location of sensors for measuring the heating effect of heat pump.*

Electrical power input to the motor of the compressor W_{input} can be measured using power meter. Measured values of Q_{cond} and W_{input} can be substituted in Eq. (7.26) to calculate the COP of the heat pump.

Cooling effect (as the by-product) produced by the heat pump can be calculated using Eq. (7.27) as:

$$Q_{eva} = Q_{cond} - W_{input}$$

$$Q_{eva} = V\rho_w C_p (T_2 - T_1) - W_{input} \tag{7.30}$$

If the cooling effect of the heat pump can be used for space cooling or process cooling (or precooling), the overall performance $COP_{overall}$ of the heat pump becomes:

$$COP_{overall} = \frac{Heating\ effect, Q_{cond}\ (kW) + Cooling\ effect, Q_{eva}\ (kW)}{Input\ power\ to\ motor\ of\ compressor, W_{input}\ (kW)} \tag{7.31}$$

$$COP_{overall} = COP_{HP} + COP_{A/C} \tag{7.32}$$

7.3.2 Measuring Sensors for Heat Pump Systems

Commonly used sensors for measuring different parameters of heat pumps are presented in Table 7.2.

Table 7.2: *Commonly used sensors for measuring different parameters of heat pumps.*

Sensor type	Parameters	Recommended accuracy
Thermistor / RTD	Temperature of hot water	± 0.05 to ± 0.1°C
Ultrasonic / full bore magnetic flowmeter	Volume flow rate of hot water	± 2%
Power meter	Compressor and pumps power consumption	± 1%.

7.4 Compressed Air Systems

Compressed air at pressure of 5 bar to 10 bar is commonly used in industrial plants for the operation of pneumatic equipment, control systems, processes and cleaning operations. It is considered as the fourth utility after electricity, water and natural gas or oil. Compression of air is an energy intensive operation. Generally, 20% to 50% of compressed air energy can be saved by system improvement, which involves the evaluation of system performance using appropriate measurements, identification and implementation of energy saving measures. The main components of a typical compressed air system are: (a) compressors, (b) filters, (c) air receivers, (d) dryers and (e) distribution systems as shown in Figure 7.17.

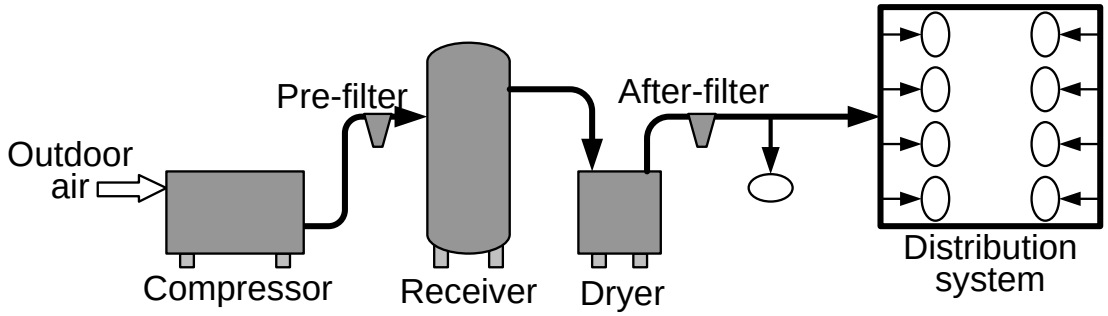


Figure 7.17: *Main components of a typical compressed air system.*

Outdoor air is drawn and compressed to the pre-set pressure by the compressors. Compressed air is filtered using pre-filters and then stored in the receiver tanks. Based on the required dryness of compressed air by the pneumatic equipment, processes and control

systems, different types of dryers are used to dry the compressed air. Finally, the compressed air is filtered again and then supplied to the equipment through a distribution system.

Learning Outcomes

Participants will be able to:

i. Understand basic operation of the compressed air systems
ii. Identify suitable energy performance indicators
iii. Identify parameters to be measured to calculate the energy performance
iv. Select locations for measuring parameters
v. Calculate energy performance of the compressed air systems
vi. Understand basic information about audit of compressed air systems

7.4.1 Types of Compressor

Reciprocating, sliding vane, lobe, screw, scroll, axial turbine and centrifugal compressors are commonly used in industrial plants. The cooling process of the compressors is classified as: (a) water cooled and (b) air cooled. Water cooled compressors are more efficient than the air cooled compressors. Depending on whether oil is used for cooling and sealing, the compressors are further classified as: (a) oil flooded type where oil is injected into compressor and (b) oil free type. Pressure ratio for the oil free compressors is relatively low. Hence, multistage oil free compressors are required for the higher pressure applications.

7.4.2 Measurement of Specific Power and FAD

Specific power and specific energy are used to represent the compressed air system supply efficiency. Specific power of compressed air system is defined as the ratio of average electric power consumption of the compressors and auxiliary supply-side equipment such as air dryers, ventilation fans, cooling pumps, cooling towers, etc. to the Free Air Delivery (FAD) rate at normal temperature of 273 K and pressure of 101.33 kPa. Frequently, local ambient temperature and pressure, other than normal temperature and pressure, is used to calculate the specific power.

$$Specific\ power = \frac{Average\ power\ consumption\ of\ compressors\ and\ auxiliary\ supply\text{-}side\ equipment, kW}{Average\ free\ air\ delivery\ rate\ at\ normal\ conditions, Nm^3/min} \quad (7.33)$$

and

$$Specific\ power = \frac{Average\ power\ consumption\ of\ compressors\ and\ auxiliary\ supply\text{-}side\ equipment, kW}{Average\ free\ air\ delivery\ rate\ at\ actual\ conditions, m^3/min}$$

(7.34)

Specific energy consumption of compressed air system, on the other hand, is defined as the ratio of the total electrical energy consumption of the compressors and auxiliary supply-side equipment such as air dryers, ventilation fans, cooling pumps, cooling towers, etc. for a specific period of time (usually 7 days) to the total Free Air Delivery (FAD) at normal or local ambient temperature and pressure during the same period of time.

$$Specific\ energy = \frac{Total\ energy\ consumption\ of\ compressors\ and\ auxiliary\ supply\text{-}side\ equipment, kWh}{Total\ free\ air\ delivery\ rate\ at\ normal\ conditions, Nm^3}$$

(7.35)

and

$$Specific\ energy = \frac{Total\ energy\ consumption\ of\ compressors\ and\ auxiliary\ supply\text{-}side\ equipment, kWh}{Total\ free\ air\ delivery\ rate\ at\ actual\ conditions, m^3}$$

(7.36)

To determine the specific power and specific energy of the compressed air system, input electrical power to the compressors and auxiliary supply-side equipment is measured using power meter and volume flow rate of compressed air at the outlet of the compressor (point-2) as shown in Figure 7.18 is measured using hot-film (thermal-dispersion) insertion probe or ultrasonic flow meter.

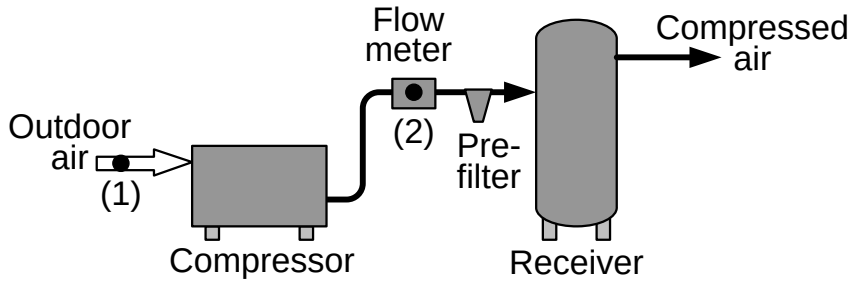


Figure 7.18: *Location of flow meter for measuring the flow rate of compressed air.*

Free air delivery rate (FAD) at the inlet of the compressor (point-1) can be calculated using ideal gas equation as:

$$\frac{V_1 P_1}{T_1} = \frac{V_2 P_2}{T_2}$$

$$V_1 = \frac{V_2 P_2 T_1}{T_2 P_1} \tag{7.37}$$

$$FAD_{actual} = \frac{V_2 P_2 T_a}{T_2 P_a} \tag{7.38}$$

$$FAD_{normal} = \frac{V_2 P_2 T_{normal}}{T_2 P_a} \tag{7.39}$$

where,

V_1 = volume flow rate of outdoor free air (FAD), m^3/min

V_2 = volume flow rate of compressed air, m^3/min

P_a = atmospheric pressure, kPa

P_2 = pressure of compressed air, kPa

T_a = temperature of ambient air, K

T_{normal} = temperature of air at normal condition, 273 K

T_2 = temperature of compressed air, K

FAD_{actual} = actual free air delivery rate, m^3/min

FAD_{normal} = free air delivery rate at normal conditions, m^3/min

Free air delivery rate can also be determined by closing the valve located after the receiver tank as shown in Figure 7.19 and operating the compressor to increase the pressure of the receiver tank to a pre-specified value. Suppose:

$V_{receiver}$ = volume of receiver tank, m^3

P_a = atmospheric pressure, kPa

T_a = temperature of ambient air, K

FAD_{actual} = actual free air delivery rate, m^3/min

$P_{initial}$ = initial pressure of receiver tank, kPa

P_{final} = final pressure of receiver tank, kPa

t = time required to increase the pressure of receiver tank from $P_{initial}$ to P_{final}, minute

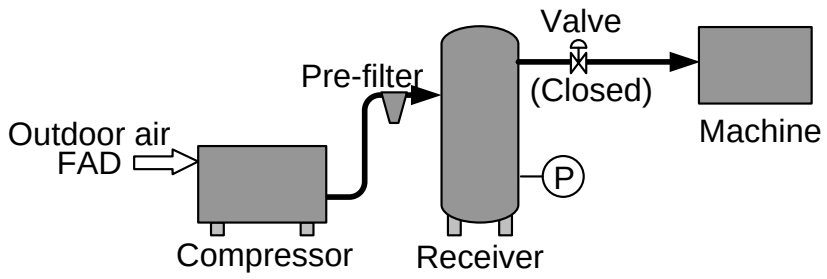


Figure 7.19: *Location of valve after the receiver tank.*

Initial mass of air ($m_{initial}$) inside the receiver tank can be calculation using the ideal gas equation as:

$$m_{initial} = \frac{P_{initial} V_{receiver}}{RT_{receiver}} \tag{7.40}$$

where,

R = gas constant, kJ/(kg K) or (kPa . m^3)/(kg K)

$T_{receiver}$ = temperature of air inside the receiver tank, K

Similarly, final mass of air (m_{final}) inside the receiver tank after time t minutes can be calculated using the ideal gas equation as:

$$m_{final} = \frac{P_{final} V_{receiver}}{RT_{receiver}} \tag{7.41}$$

Mass flow balance of air for the compressor and receiver tank gives:

$$P_a (FAD_{actual}) t = mRT_a$$

$$P_a (FAD_{actual}) t = \left(m_{final} - m_{initial}\right) RT_a \tag{7.42}$$

Combining Eqs. (7.40), (7.41) and (7.42) gives:

$$FAD_{actual} = \frac{T_a \left(P_{final} - P_{initial}\right) V_{receiver}}{P_a T_{receiver} t} \tag{7.43}$$

7.4.3 Measurement of Utilisation Factor

Utilisation factor is used for sizing the compressed air system for the total air requirements of the industrial plant. It is defined as the ratio of actual consumption of compressed air of the industrial processes to the rated maximum continuous consumption over 24 hours.

$$Utilization\ Factor = \frac{Actual\ compressed\ air\ consumption\ in\ 24\ hrs}{Maximum continuous\ consumption\ in\ 24\ hrs} \tag{7.44}$$

Actual consumption of the compressed air in 24 hours can be measured by installing the hot-film (thermal-dispersion) insertion probe or ultrasonic flow meter after the compressor as presented in section 7.4.2 and Figure 7.18. Compressed air consumption rate should be trend

logged at time interval of Δt (say 10 seconds) for 24 hours and actual consumption of the compressed air in FAD for 24 hours can be calculated by integrating Eq. (7.37) as:

$$Compressed\,air\,consumption\,in\,FAD = \sum V_1 \Delta t = \sum \frac{V_2 P_2 T_1 \Delta t}{T_2 P_1} \tag{7.45}$$

Rated maximum continuous consumption of compressed air by the industrial processes over 24 hours can be determined from the technical specifications of the industrial processes and equipment.

7.4.4 Measurement of Air Leaks

Compressed air leaks are the greatest single cause of energy loss for the compressed air system. In general, air leaks occur at joints, flange connections, elbows, reducing bushes, sudden expansions, filters, hoses, check valves, relief valves, expansions, regulators and the equipment connected to the compressed-air lines. Total elimination of the air leaks is impractical. A leakage rate of below 5% is generally considered acceptable.

To determine the leakage rate of compressed air, the valve located after the receiver tank as shown in Figure 7.20 should be kept open and the equipment that use the compressed air should be switched off. Under this condition the compressor should be turned on to charge the compressed air system to the pre-set operating pressure. Once the pressure reaches to the pre-set operating pressure, the compressor will be turned off. Due to the leakage of air, the pressure of the compressed air system will drop gradually and reach the pre-set lower limit. Once the pressure drops to the pre-set lower pressure, the compressor will be turned on again and the cycle is repeated. The time taken for the “load” and “unload” cycles should be measured continuously for about 10 cycles.

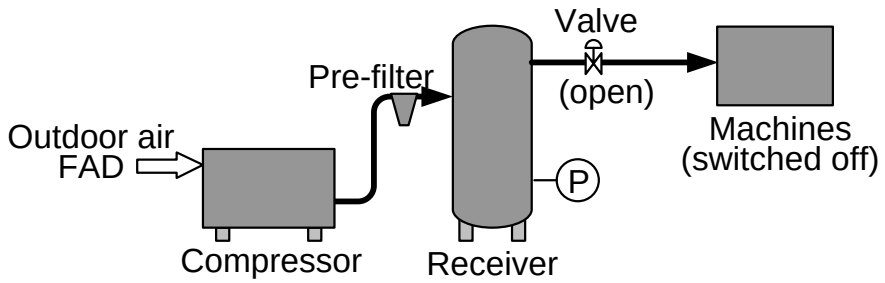


Figure 7.20: *Valves are kept open and machines are switched off.*

Percentage of compressed air leakage can be calculated as:

$$\%\ of\ \ compressed\ air\ leakage = 100\left(\frac{T}{T+t}\right) \tag{7.46}$$

where,

T = average load time, minutes

t = average unload time, minutes

Leakage rate of the compressed air can be calculated as:

$$Leakage\ rate\ of\ \ compressed\ air = Q\left(\frac{T}{T+t}\right) \tag{7.47}$$

where,

Q = compressor operating capacity in FAD, m^3/minute

Ultrasonic leak detectors and soap bubble are commonly used to identify the locations of leaks.

7.4.5 Measurement of Temperature and Pressure for Energy Savings

If a compression process is adiabatic (compressor is perfectly insulated resulting no heat loss) and the compressor is reversible (ideal frictionless compressor), the process is called isentropic compression process. Power input to the isentropic compression processes can be is calculated as:

$$W_{isen} = \frac{m_a kR(T_2 - T_1)}{k-1} = \frac{m_a kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.48}$$

where,

W_{isen} = input power to isentropic compression process, kW

m_a = mass flow rate of compressed air, kg/s

R = gas constant, kJ/(kg K) or (kPa . m^3)/(kg K)

T_1 = temperature of air at the inlet of compressor, K

T_2 = temperature of air at the outlet of compressor, K

P_1 = pressure of air at the inlet of compressor, kPa

P_2 = pressure of air at the outlet of compressor, kPa

$K = C_p/C_v$ = ratio of specific heat, dimensionless

C_p = specific heat of air at constant pressure, kJ/(kg K)

C_v = specific heat of air at constant volume, kJ/(kg K)

C_p, C_v and k are function of temperature. They should be calculated for the average compressing process temperature. The ratio of input power to the isentropic compressor and the actual compressor is called isentropic efficiency.

$$Isentropic\ efficiency, \eta_{isen} = \frac{Input\ power\ to\ isentropic\ compressor}{Input\ power\ to\ actual\ compressor} \tag{7.49}$$

Therefore, power input to the actual compressor W_{ac} is:

$$Input\ power\ to\ actual\ compressor, W_{ac} = \frac{Input\ power\ to\ isentropic\ compressor}{Isentropic\ efficiency, \eta_{isen}} \tag{7.50}$$

$$W_{ac} = \frac{m_a kR(T_2 - T_1)}{\eta_{isen}(k-1)} = \frac{m_a kRT_1}{\eta_{isen}(k-1)}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.51}$$

Input power to the motor of the compressor $W_{m,in}$ (as shown in Figure-7.21) can be calculated as:

$$W_{m,in} = \frac{m_a kR(T_2 - T_1)}{\eta_m \eta_g \eta_{isen}(k-1)} = \frac{m_a kRT_1}{\eta_m \eta_g \eta_{isen}(k-1)}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.52}$$

where,

$W_{m,in}$ = input power to the motor of compression, kW

η_m = efficiency of motor, dimensionless

η_g = efficiency of gear box, dimensionless

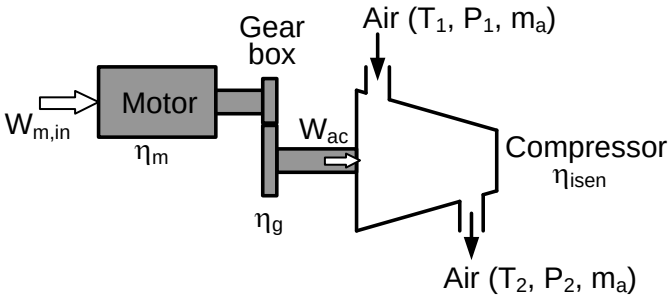


Figure 7.21: *Coupling of motor with compressor.*

Eq. (7.52) shows that input power to the motor of the compressor decreases with the decrease of inlet air temperature T_1 and compressor outlet pressure P_2. T_1 and P_2 should be measured using appropriate temperature sensor and pressure transducer and opportunities for the

reduction of T_1 and P_2 should be identified for potential reduction of the input power of the compression systems.

For inlet air temperature of T_1', input power to the motor of the compressor:

$$W_{m,in@T_1'} = \frac{m_a k R T_1'}{\eta_m \eta_g \eta_{isen}(k-1)}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.53}$$

For inlet air temperature of T_1'', input power to the motor of the compressor:

$$W_{m,in@T_1''} = \frac{m_a k R T_1''}{\eta_m \eta_g \eta_{isen}(k-1)}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.54}$$

Percentage reduction of compressor power consumption due to the decrease of intake air temperature from T_1' to T_1'':

$$\frac{W_{m,in@T_1'} - W_{m,in@T_1''}}{W_{m,in@T_1'}} x100 = \left(1 - \frac{T_1''}{T_1'}\right) x100 \tag{7.55}$$

where,

T_1' = present temperature of air at the inlet of compressor, K

T_1'' = proposed new temperature of air at the inlet of compressor, K

Similarly, for compressor outlet pressure of P_2', input power to the motor of the compressor:

$$W_{m,in@P_2'} = \frac{m_a k R T_1}{\eta_m \eta_g \eta_{isen}(k-1)}\left[\left(\frac{P_2'}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.56}$$

For compressor outlet pressure of P_2'', input power to the motor of the compressor:

$$W_{m,in@P_2''} = \frac{m_a k R T_1}{\eta_m \eta_g \eta_{isen}(k-1)}\left[\left(\frac{P_2''}{P_1}\right)^{(k-1)/k} - 1\right] \tag{7.57}$$

Percentage reduction of compressor power consumption due to the decrease of compressor outlet pressure from P_2' to P_2'':

$$\frac{W_{m,in@P_2'} - W_{m,in@P_2''}}{W_{m,in@P_2'}} x100 = 100x\left[1 - \frac{\left(\frac{P_2''}{P_1}\right)^{(k-1)/k} - 1}{\left(\frac{P_2'}{P_1}\right)^{(k-1)/k} - 1}\right] \tag{7.58}$$

where,

P_2' = present pressure of air at the inlet of compressor, kPa

P_2'' = proposed new pressure of air at the inlet of compressor, kPa

Required pressure of compressed air for the pneumatic equipment, systems and processes should be determined from the respective technical specifications. Pressure loss for the piping systems including associated fittings can be measured using pressure gauge. Compressor outlet pressure should be set to the minimum possible value to overcome the losses of the piping systems and maintain the design pressure for the pneumatic equipment, systems and processes.

7.4.6 Measurement of Dryness of Compressed Air

Moisture of compressed air may damage the pneumatic equipment and affect the performance of the systems or processes. If air is compressed, moisture holding capacity of the compressed air drops. Hence, certain percentage of moisture is condensed as the air is compressed. Based on the required dryness of compressed air for the pneumatic equipment or processes involved, compressed air is further dried using different types of dryers (such as direct expansion refrigerant dryers and desiccant dryers) before being supplied to the pneumatic equipment or processes. Dryness of the compressed air is normally expressed in "dew point". The temperature at which the moisture of the compressed air starts to condense is called dew point. Dew point temperature decreases with the decrease of moisture content of the compressed air as presented in Table 7.3. Dew point sensors are used to measure the dew point and corresponding moisture content of the compressed air after the dryers. Power consumption of the compressors of direct expansion type refrigerant dryers and volume flow rate of purging air for the desiccant dryers should be measured to evaluate the performance of the dryer systems. As discussed in earlier sections, power meters are used to trend log the power consumption of the compressors of refrigerant dryers and hot-film (thermal-dispersion) insertion probe or ultrasonic flow meter are installed at the inlet of the regenerating desiccant columns of desiccant dryers to trend log the volume flow rate of purging air.

Table 7.3: *Variation of dew point with moisture contents of air*

Dew point at atmospheric pressure, ^{o}C	Amount of moisture (ppm)
0	3800
-5	2500
-10	1600
-20	685
-30	234

7.4.7 Measuring Sensors for Compressed Air Systems

Commonly used sensors for measuring different parameters of compressed air systems are presented in Table 7.4.

Table 7.4: *Commonly used sensors for measuring different parameters of compressed air systems.*

Sensor type	Parameters	Recommended accuracy
RTD / Thermocouples	Temperature of compressed air	± 0.1 to ± 0.5°C
Hot-film (thermal-dispersion) insertion probe or ultrasonic flow meter	Volume or mass flow rate of compressed air	± 2%
Power meters	Power consumption of motor of compressors	± 1%.
Pressure gauge / Pressure transducer	Pressure of compressed air	± 0.5%
Dew point sensors	Moisture content of compressed air	± 2.0°C

8 Data Plotting and Analysis Assignments

To achieve a sustainable built environment, it is important that buildings continue to operate efficiently throughout their life cycle. Under the Building Control Act, BCA may serve a notice to building owners to carry out a periodic energy audit of their chiller plant system every 3 years. Upon receipt of the notice, building owners are required to engage a Professional Mechanical Engineer or an Energy Auditor registered with BCA to carry out the energy audit and submit the complying energy audit results to BCA by the deadline stipulated in the Notice. For more information please visit:
https://www.bca.gov.sg/EnvSusLegislation/Existing_Building_Legislation.html

The energy audit report will present the performance of the centralised chilled water system efficiency based on the measurements from the permanent instrumentations installed on site. In this chapter you will learn how to prepare the energy audit report using Excel.

Important Excel tools/commands to be familiar with while preparing energy audit report

a. Count
b. Count if
c. Plotting of line chart
d. Plotting of scatter chart
e. Plotting of histogram

Learning Outcomes

Participants will be able to:

i. Prepare the Operating System Efficiency (OSE) report
ii. Draw charts that are needed for the energy audit report
iii. Calculate chilled water system efficiency
iv. Check that the heat balance percentage is within +/- 5%

8.1 Formulae

Insert data from the raw data sheet into formulae 1 to 9 below.

Raw data sheet can be downloaded from below link

https://ies.org.sg/iesa/scem/example_raw_data.xlsx

1. CHW Load (KW) = 4.19 * Flow (l/s) * Δ T (°C)
2. CHW Load (RT) = CHW Load (KW) /3.517
3. CDW heat rejection (KW) = 4.19 * Flow (l/s) * Δ T (°C)
4. CDW heat rejection (RT) = CDW heat rejection (KW)/3.517
5. Total Chilled water plant Power (KW) = sum of all KW within the plant (CH Total Power KW + CHWP Total Power KW + CDWP Total Power KW + CT Total Power KW)
6. Chilled water plant Efficiency = Total Chilled water plant Power (KW)/ CHW Load (RT)
7. Heat in (KW) = Chiller Total Power (KW) + CHW Load (KW)
8. Heat out (KW) =CDW heat rejection (KW)
9. Heat Balance error (%) = (Heat in – Heat out) / Heat out

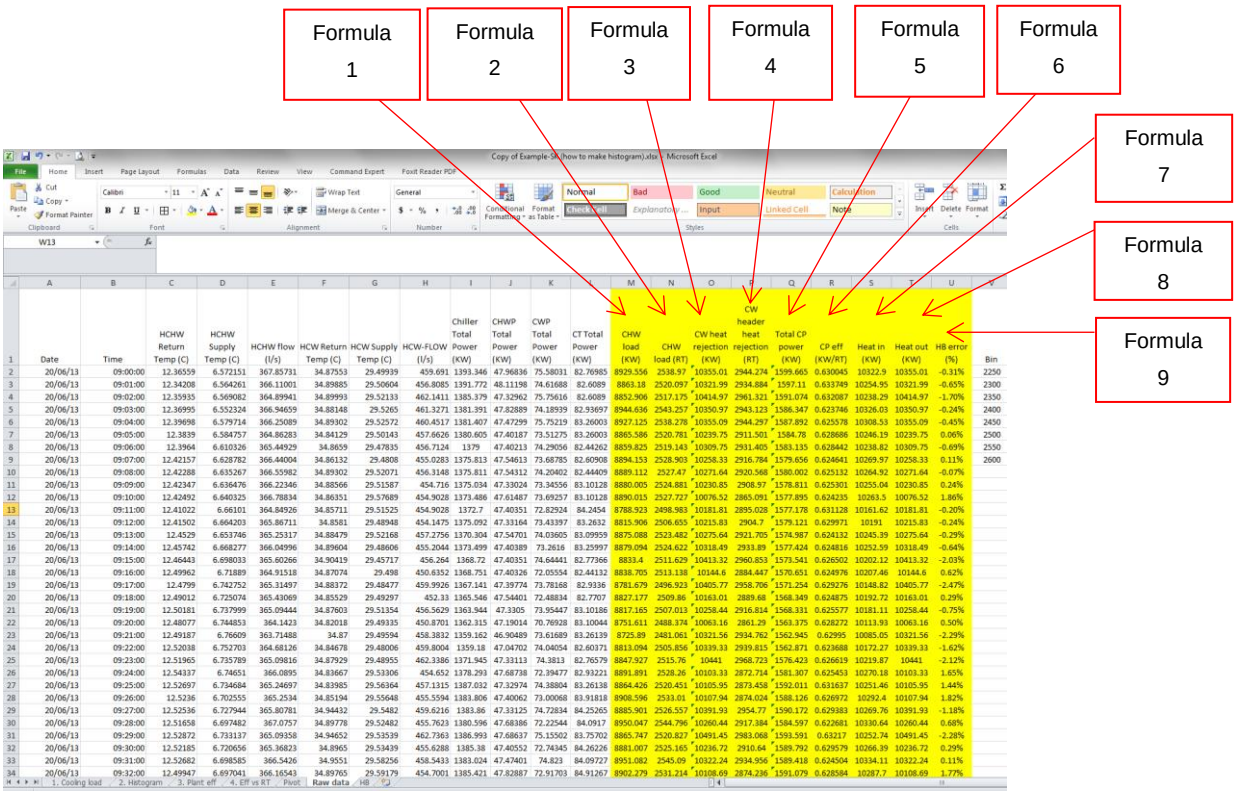


Figure 8.1: *Formulae and raw data sheet to compute various parameters*

8.2 Cooling Load (RT)

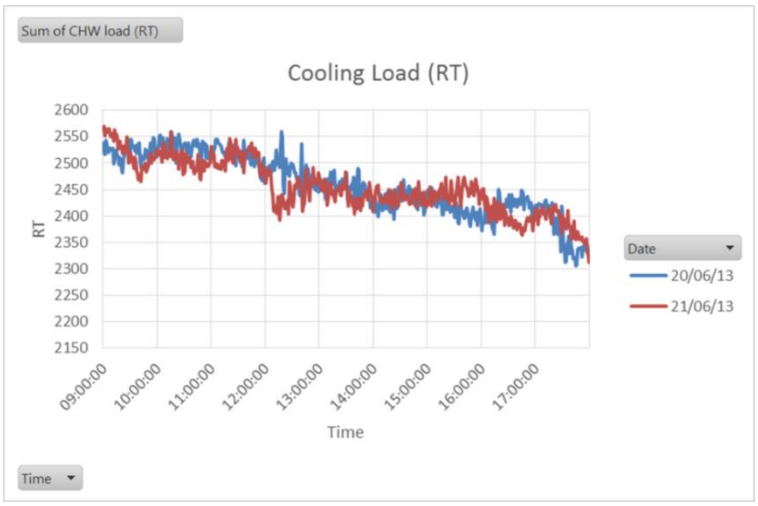


Figure 8.2: *Cooling Load (RT) Profile*

To draw the Pivot chart, there should not be any empty rows, columns or cells within the data.

Step 1: To create a Pivot Chart, put the cursor at any place within the data. Go to the **Insert** tab > Select **PivotChart**

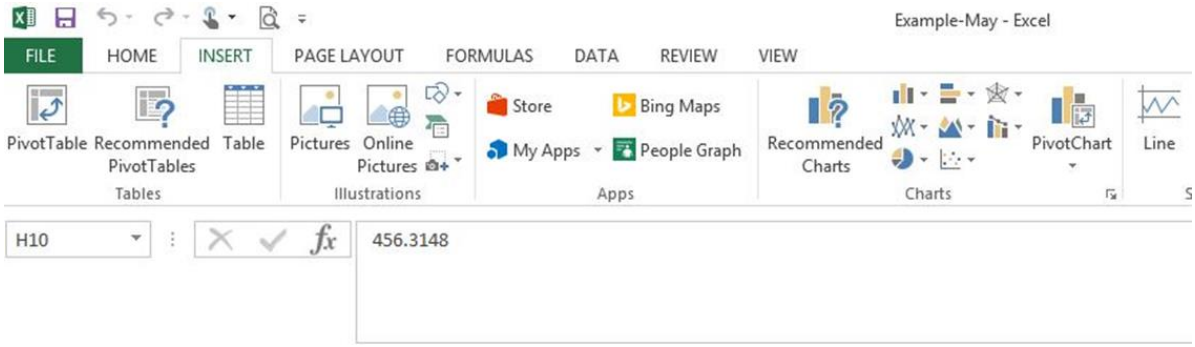


Figure 8.3: *Pivot chart*

Step 2: **Create Pivot Chart** box will open up after the step 1. To select the range > Select **a table or range** and it will select all the data > Select **New worksheet**

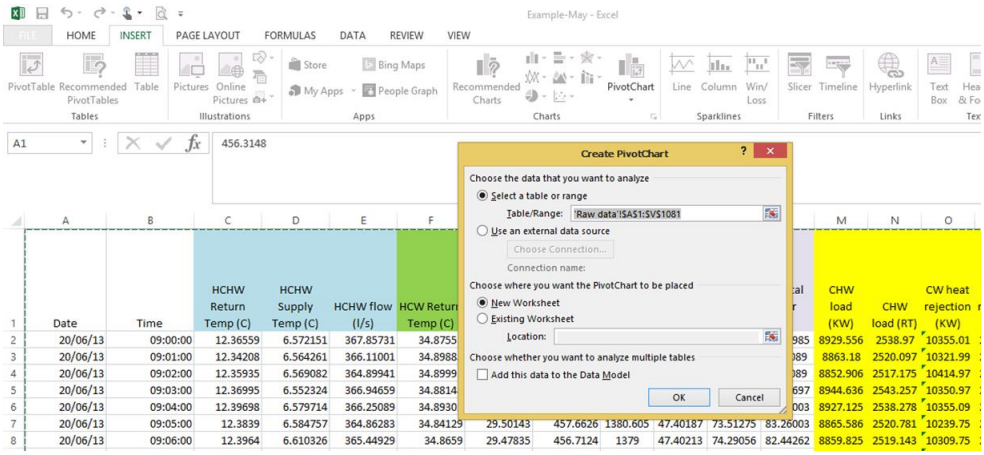


Figure 8.4: *Create Pivot Chart*

Step 3: **Rename** the new work sheet as Pivot. Add in the x-axis and y-axis values. **Drag** the pivot table fields to respective areas (see in step 4).

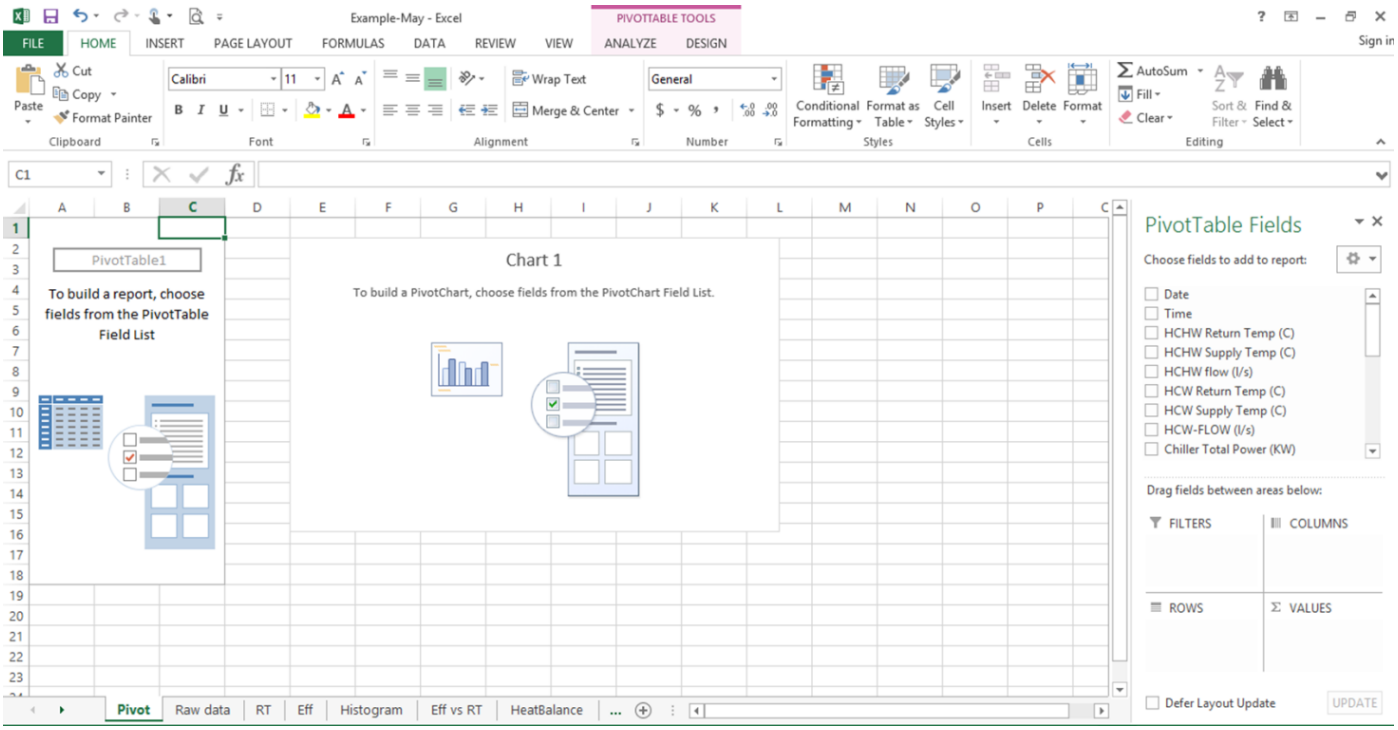


Figure 8.5: *Pivot Chart*

Step 4: Drag **Time** to AXIS, **Date** as LEGEND, **CHW Load RT** to VALUES.

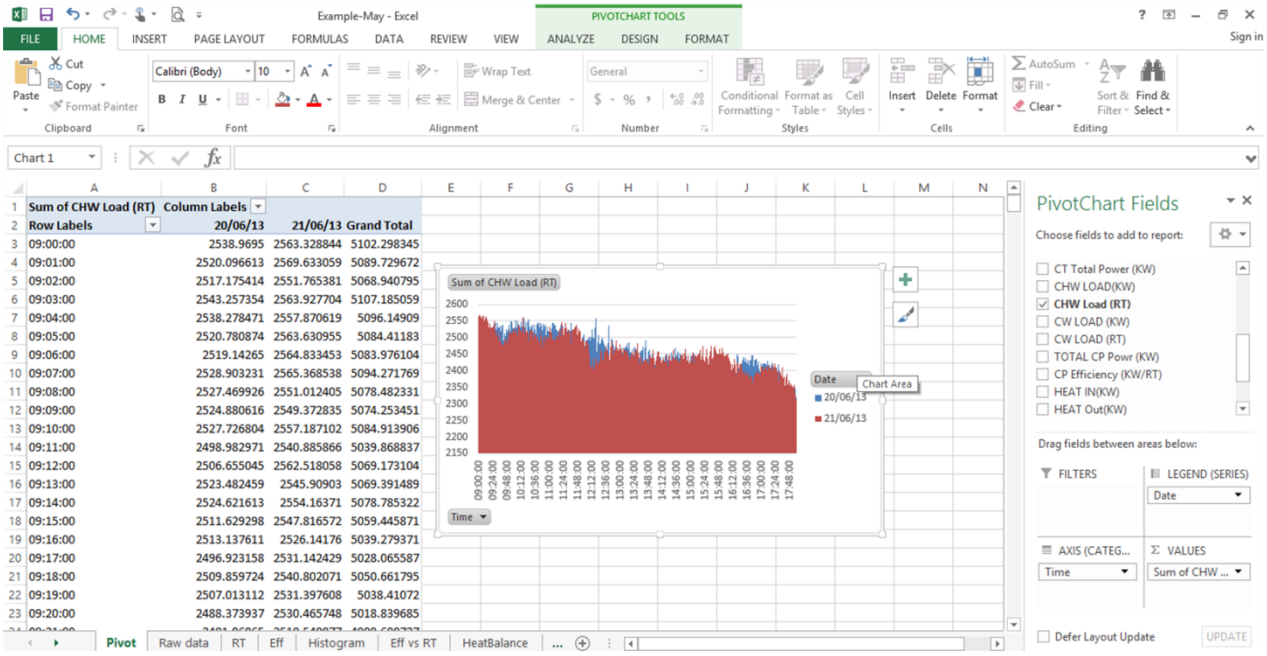


Figure 8.6: *Pivot Chart*

Step 5: To change the chart type >Right click on the chart, Select **change chart type**, select **Line** chart type as shown below.

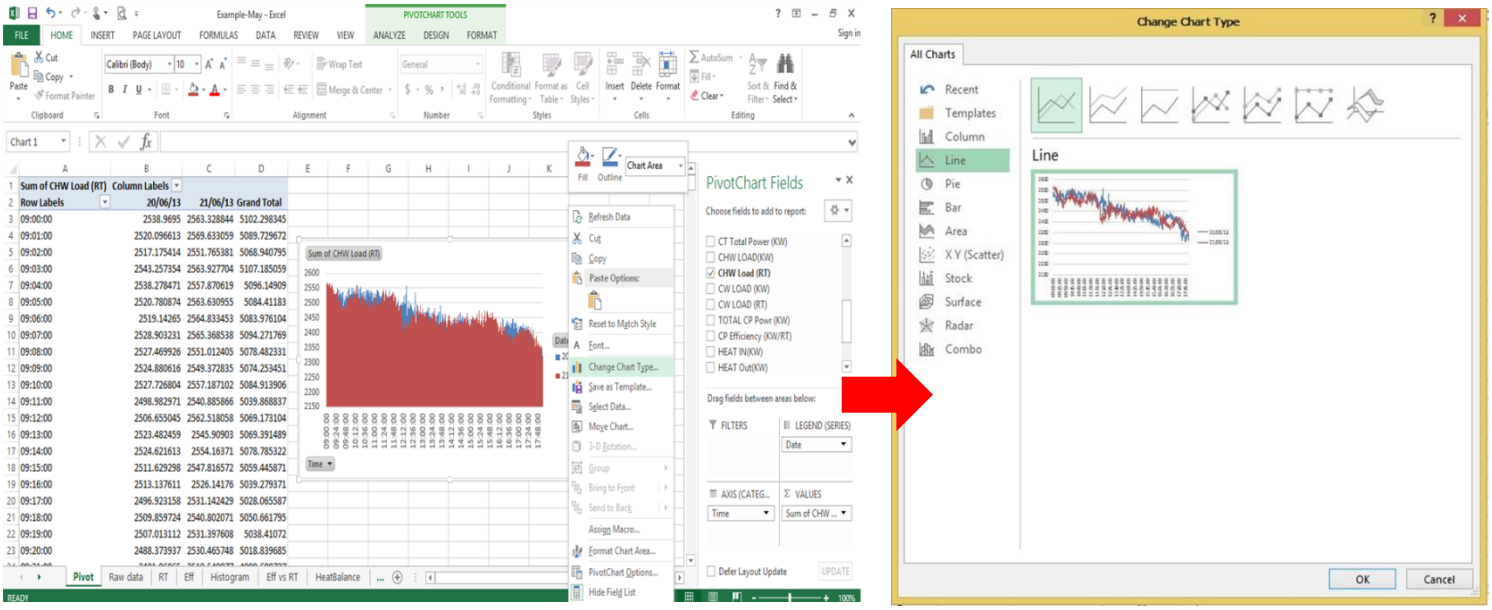


Figure 8.7: *Pivot Chart*

8.3 Frequency of Cooling Load Occurrence

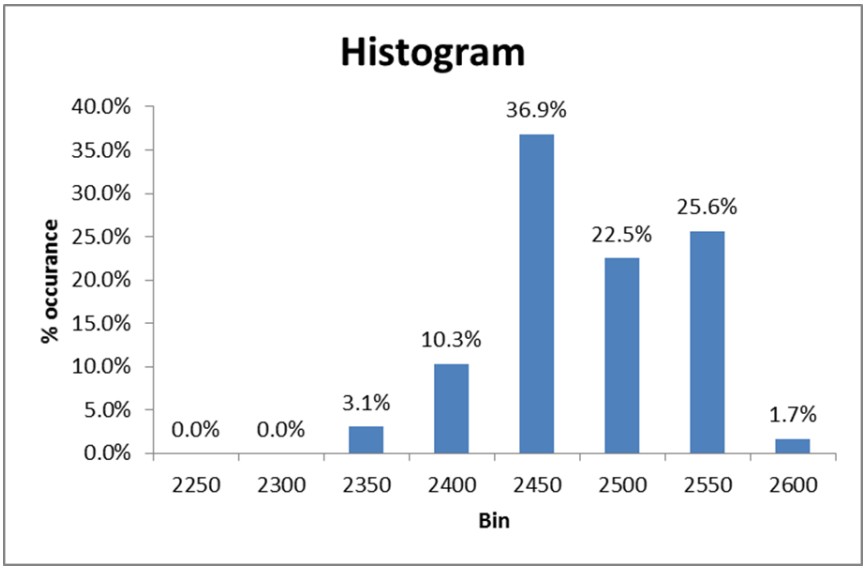
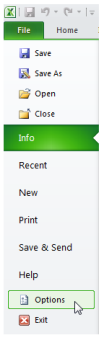


Figure 8.8: *Histogram*

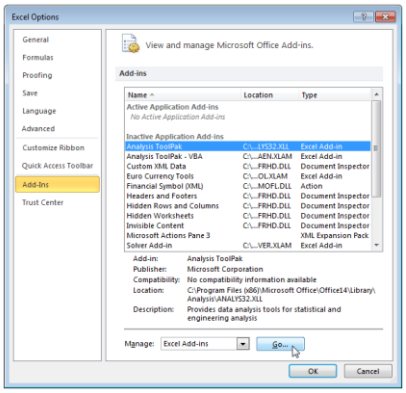
Frequency of cooling load occurrence (Histogram chart) will be plotted out by using data analysis Tool Pak.

To use the **Analysis Tool Pak in Excel**, however, you need to load it first.

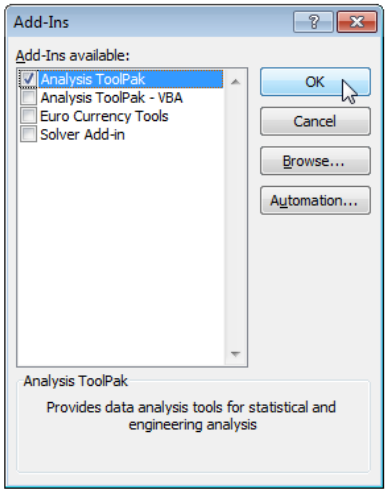
1. Click on Excel Options.



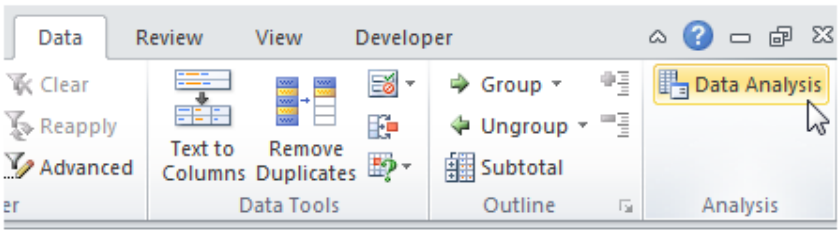
2. Under Add-Ins, click on Analysis Tool Pak, and then click on the Go button.



3. Check Analysis Tool Pak and click on **OK**.



4. Data Analysis function is available in the Analysis group on the Data tab.



Step 1: To create Histogram Chart, go to the **Data** tab, select **Data Analysis** > Select **Histogram** and click **OK**.

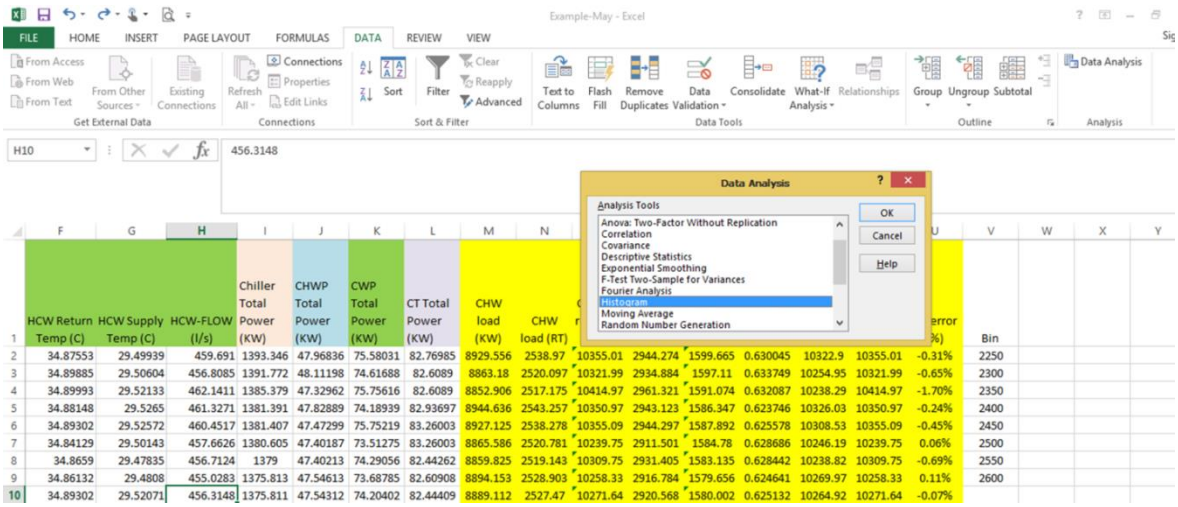


Figure 8.9: Histogram

Step 2: To Select the **Range** for histogram (**Input Range**: CHW Load RT), **Bin Range** (Bin) and save the new worksheet as Histogram.

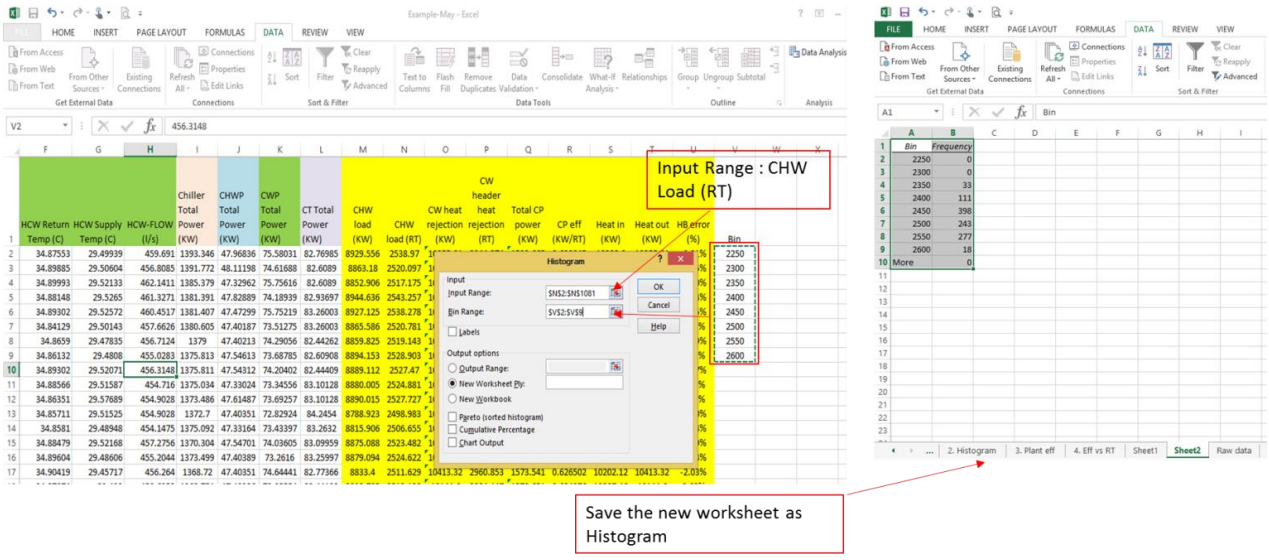


Figure 8.10: Histogram

Step 3: To calculate the Percentage Occurrence, sum the Total Frequency and **freeze the cells** B10 by using $ sign; Find the **% Occurrence** by dividing the frequency with Total.

Step 4: To plot the histogram chart, select the **% Occurrence**, click on the **insert tab**, select **Histogram 2-D** chart.

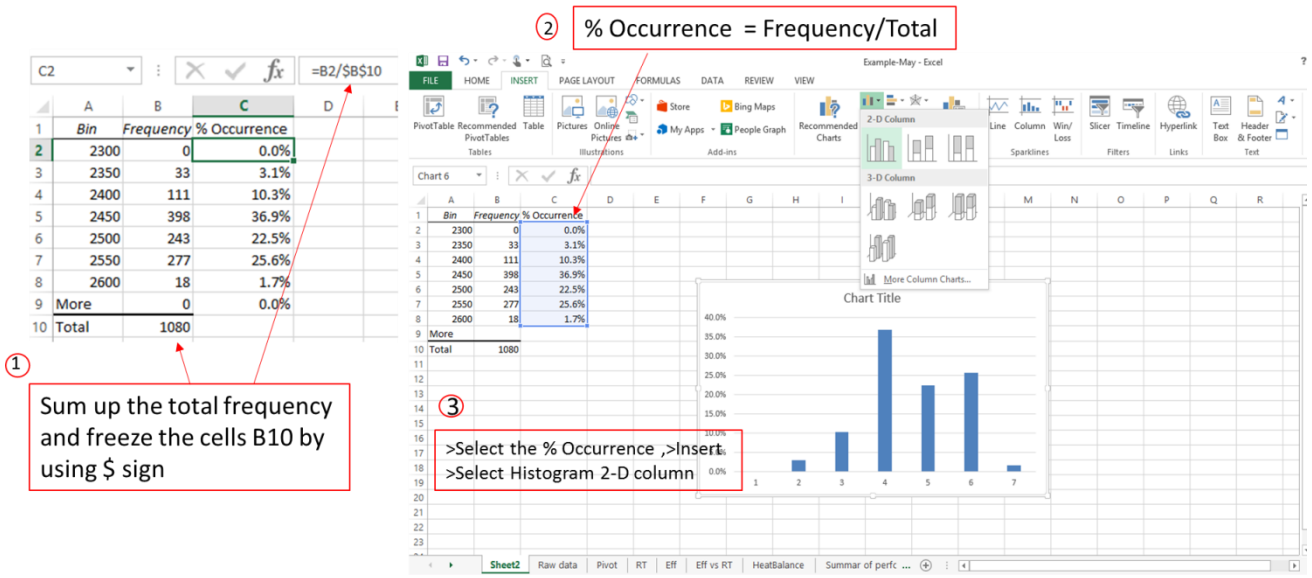


Figure 8.11: Histogram

Step 5: To change the Axis Labels> **Right click** on the chart, **Select Data**, click on **Edit**, select the Bin Range as Axis labels.

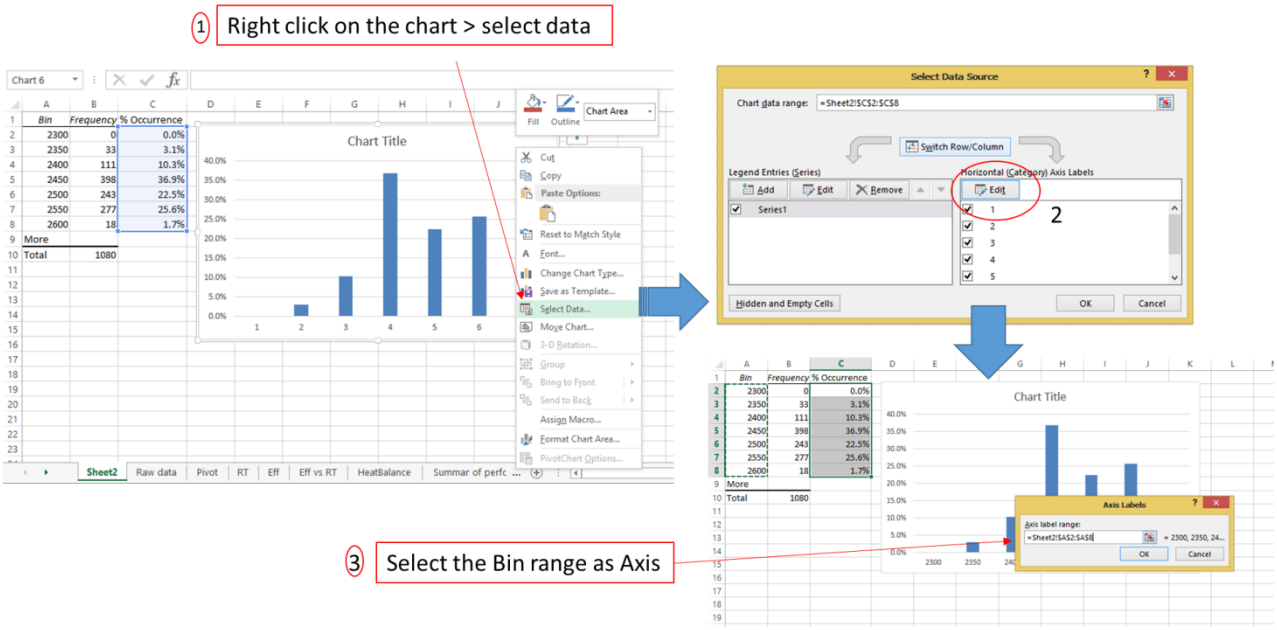


Figure 8.12: *Histogram*

8.4 Plant Efficiency (KW/RT)

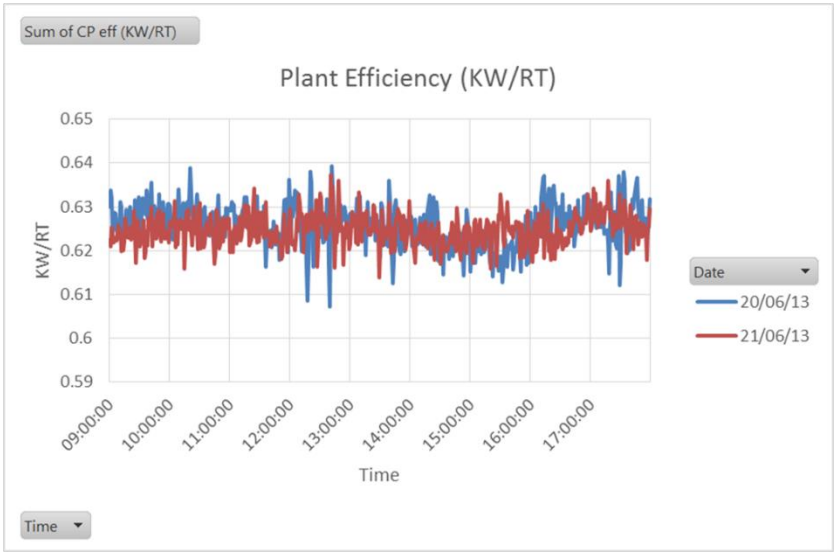


Figure 8.13: *Plant Efficiency (KW/RT)*

Step 1: To plot the plant efficiency (KW/RT) chart, go back to the **Pivot Sheet**, click on the **pivot chart** and pivot chart field box will appear. **Remove** the CHW Load RT from Values box and **drag** the CP Efficiency (KW/RT) to values box.

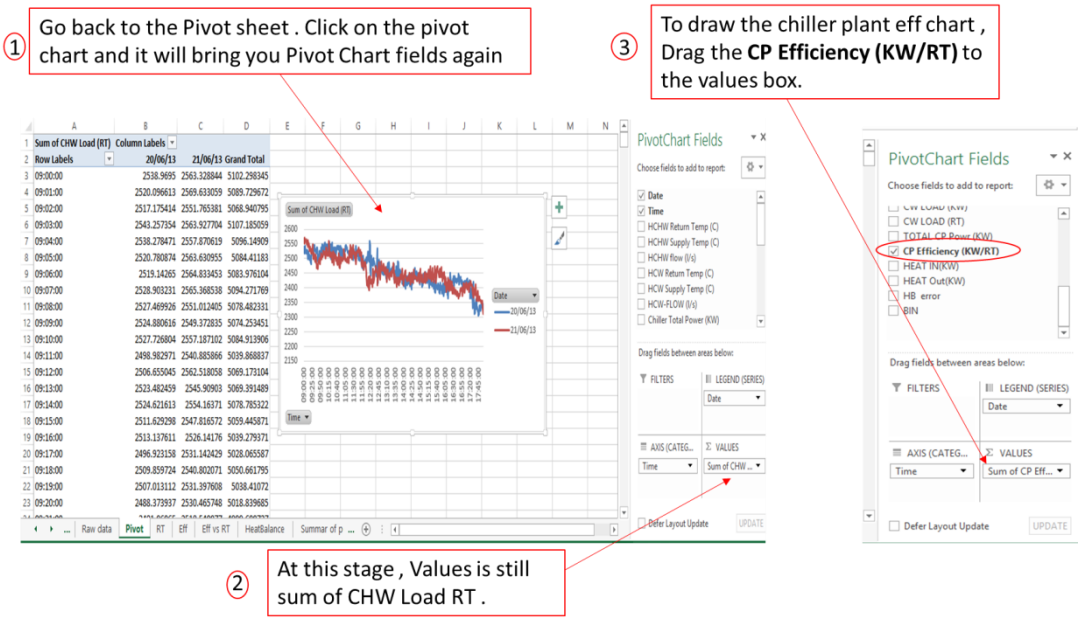


Figure 8.14: *Plant Efficiency (KW/RT)*

Step 2: To adjust the minimum and maximum Axis Range by, right click on **Format Axis,** choose **Axis Option** and set the maximum and minimum point accordingly.

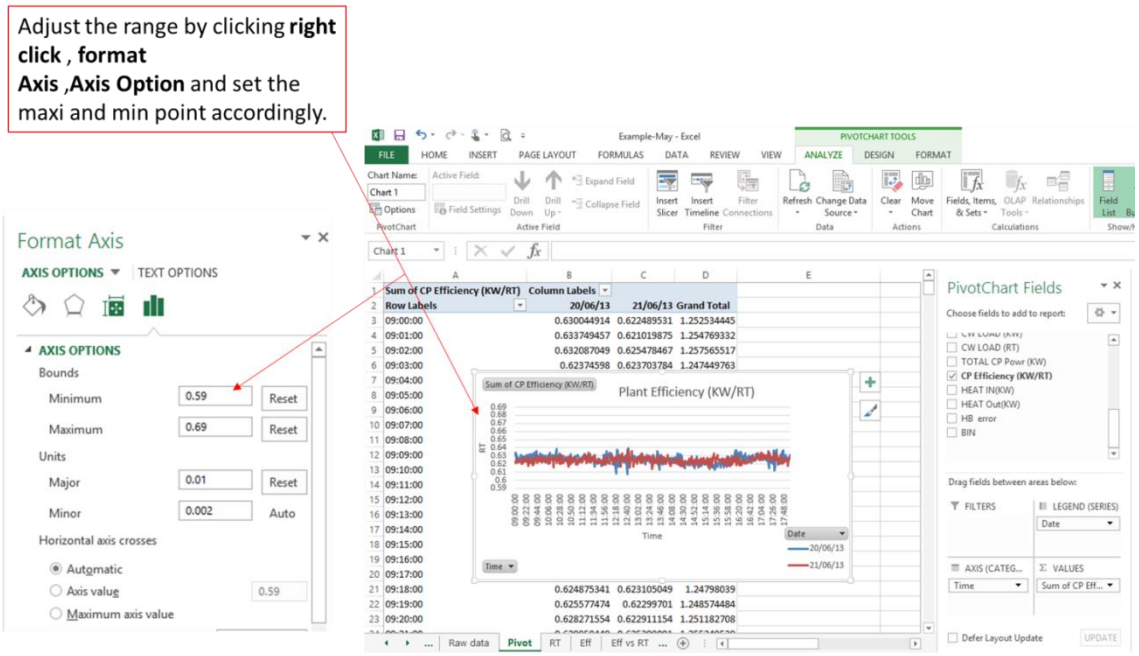


Figure 8.15: *Plant Efficiency (KW/RT)*

8.5 Efficiency (KW/RT) vs Cooling Load (RT)

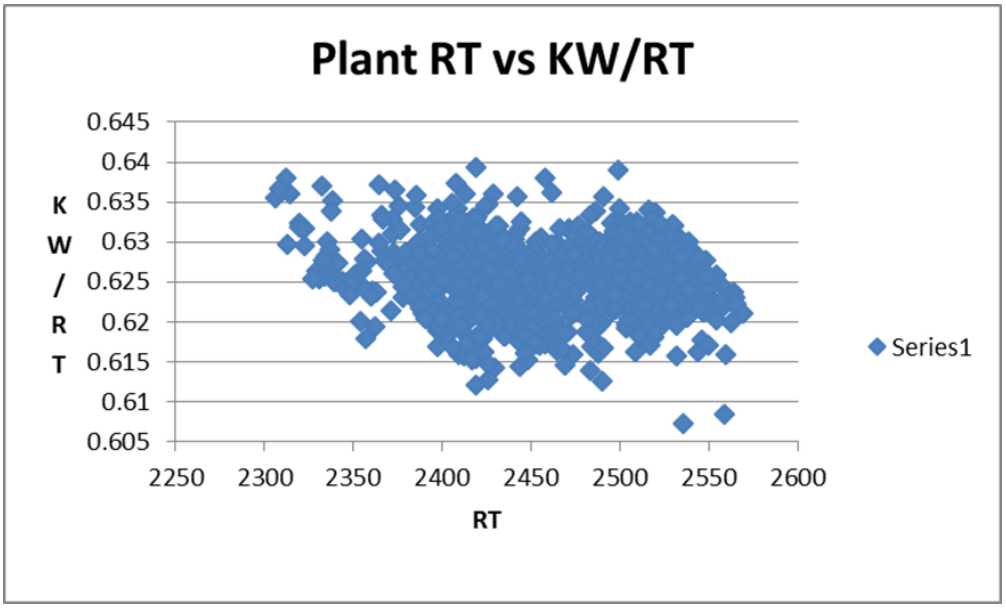


Figure 8.16: *Efficiency (KW/RT) vs Cooling Load (RT)*

Step 1: To Plot the Efficiency vs RT chart, select the entire CHW Load (RT) column and CP Efficiency (KW/RT) column.

To draw Efficiency vs RT chart , Select CHW Load (RT) entire column by using Ctrl +Shift + ⬇ and not releasing the Ctrl key select another entire column of CP Efficiency (KW/RT) by using Ctrl+Shift + ⬇

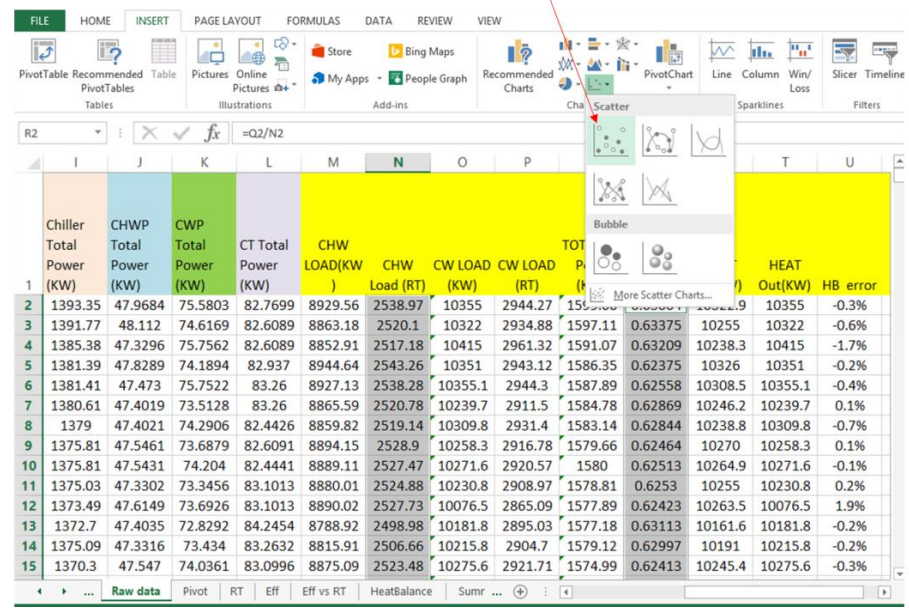
Chiller Total Power (KW)	CHWP Total Power (KW)	CWP Total Power (KW)	CT Total Power (KW)	CHW LOAD(KW)	CHW Load (RT)	CW LOAD (KW)	CW LOAD (RT)	TOTAL CP Powr (KW)	CP Efficiency (KW/RT)	HEAT IN(KW)	HEAT Out(KW)	HB error
1393.35	47.9684	75.5803	82.7699	8929.56	2538.97	10355	2944.27	1599.66	0.63004	10322.9	10355	-0.3%
1391.77	48.112	74.6169	82.6089	8863.18	2520.1	10322	2934.88	1597.11	0.63375	10255	10322	-0.6%
1385.38	47.3296	75.7562	82.6089	8852.91	2517.18	10415	2961.32	1591.07	0.63209	10238.3	10415	-1.7%
1381.39	47.8289	74.1894	82.937	8944.64	2543.26	10351	2943.12	1586.35	0.62375	10326	10351	-0.2%
1381.41	47.473	75.7522	83.26	8927.13	2538.28	10355.1	2944.3	1587.89	0.62558	10308.5	10355.1	-0.4%
1380.61	47.4019	73.5128	83.26	8865.59	2520.78	10239.7	2911.5	1584.78	0.62869	10246.2	10239.7	0.1%
1379	47.4021	74.2906	82.4426	8859.82	2519.14	10309.8	2931.4	1583.14	0.62844	10238.8	10309.8	-0.7%
1375.81	47.5461	73.6879	82.6091	8894.15	2528.9	10258.3	2916.78	1579.66	0.62464	10270	10258.3	0.1%
1375.81	47.5431	74.204	82.4441	8889.11	2527.47	10271.6	2920.57	1580	0.62513	10264.9	10271.6	-0.1%
1375.03	47.3302	73.3456	83.1013	8880.01	2524.88	10230.8	2908.97	1578.81	0.6253	10255	10230.8	0.2%
1373.49	47.6149	73.6926	83.1013	8890.02	2527.73	10076.5	2865.09	1577.89	0.62423	10263.5	10076.5	1.9%
1372.7	47.4035	72.8292	84.2454	8788.92	2498.98	10181.8	2895.03	1577.18	0.63113	10161.6	10181.8	-0.2%
1375.09	47.3316	73.434	83.2632	8815.91	2506.66	10215.8	2904.7	1579.12	0.62997	10191	10215.8	-0.2%
1370.3	47.547	74.0361	83.0996	8875.09	2523.48	10275.6	2921.71	1574.99	0.62413	10245.4	10275.6	-0.3%

Raw data | Pivot | RT | Eff | Eff vs RT | HeatBalance | Sumr

Figure 8.17: *Efficiency (KW/RT) vs Cooling Load (RT)*

Step 2: Go to **Insert** Tab, choose the **Scatter** chart type to create Plant Efficiency vs Cooling Load chart

Insert > Scatter chart type > select as per below pic



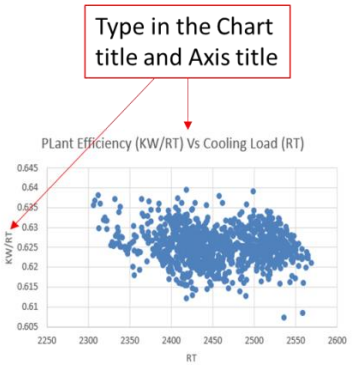


Figure 8.18: *Efficiency (KW/RT) vs Cooling Load (RT)*

8.6 Heat Balance Percentage

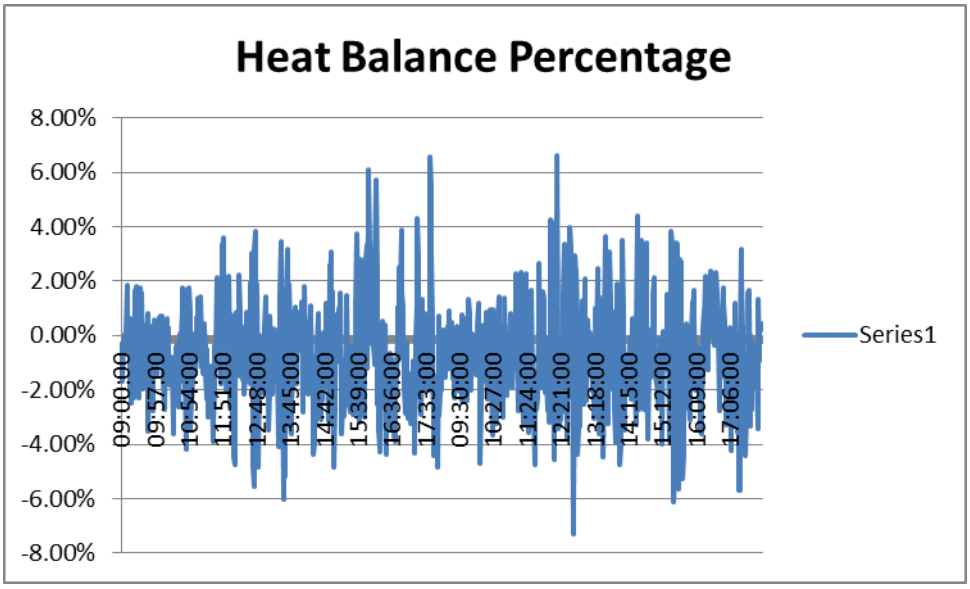


Figure 8.19: *Heat Balance Percentage*

Step 1: To plot the heat balance percentage graph, go back to the raw data sheet, **select** the **HB** error (%) column by using ctrl + Shift + ⬇

Without releasing the ctrl key, select the **Time** column by using ctrl + shift + ⬇ again.

Step 2: To create a chart, after two columns has selected, go to **Insert**, choose **Line**, **2-D line** chart.

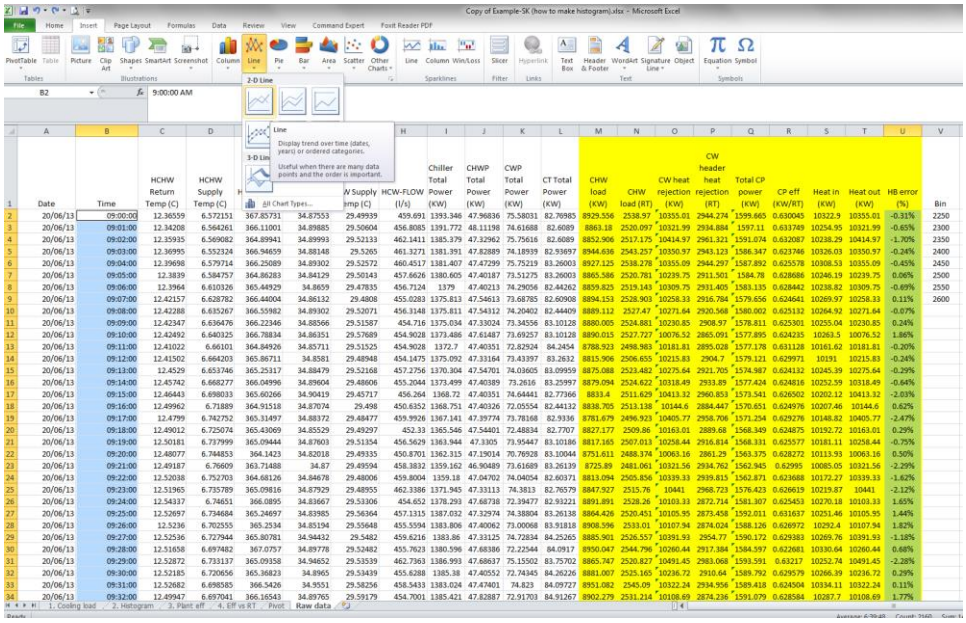


Figure 8.20: *Heat Balance Percentage*

8.7 Summary of Performance Table

Step 1: To create a Summary of Performance Table, calculate the **No 1 to 9** from summary of performance table by **using the equation below**.

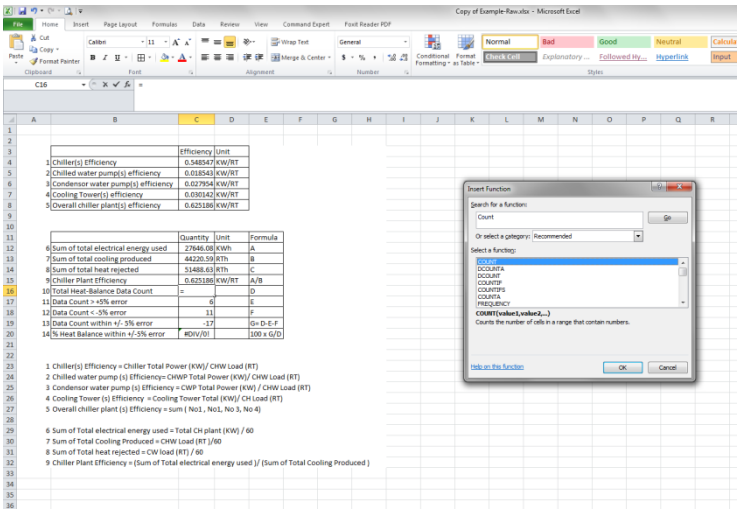
		Efficiency	Unit
1	Chiller(s) Efficiency	0.548547	KW/RT
2	Chilled water pump(s) efficiency	0.018543	KW/RT
3	Condensor water pump(s) efficiency	0.027954	KW/RT
4	Cooling Tower(s) efficiency	0.030142	KW/RT
5	Overall chiller plant(s) efficiency	0.625186	KW/RT

		Quantity	Unit	Formula
6	Sum of total electrical energy used	27646.08	KWh	A
7	Sum of total cooling produced	44220.59	RTh	B
8	Sum of total heat rejected	51488.63	RTh	C
9	Chiller Plant Efficiency	0.625186	KW/RT	A/B
10	Total Heat-Balance Data Count			D
11	Data Count > +5% error	6		E
12	Data Count < -5% error	11		F
13	Data Count within +/- 5% error	-17		G= D-E-F
14	% Heat Balance within +/-5% error	#DIV/0!		100 x G/D

1 Chiller(s) Efficiency = Chiller Total Power (KW)/ CHW Load (RT)
2 Chilled water pump (s) Efficiency= CHWP Total Power (KW)/ CHW Load (RT)
3 Condensor water pump (s) Efficiency = CWP Total Power (KW) / CHW Load (RT)
4 Cooling Tower (s) Efficiency = Cooling Tower Total (KW)/ CH Load (RT)
5 Overall chiller plant (s) Efficiency = sum (No1 , No1, No 3, No 4)

6 Sum of Total electrical energy used = Total CH plant (KW) / 60
7 Sum of Total Cooling Produced = CHW Load (RT)/60
8 Sum of Total heat rejected = CW load (RT) / 60
9 Chiller Plant Efficiency = (Sum of Total electrical energy used)/ (Sum of Total Cooling Produced)

Step 2: To count the Total Heat-Balance Data (No 10), use the **Count** function from FX, select Count from **Insert Function**, click **Go** button, click on the **Value 1** box to select the data.



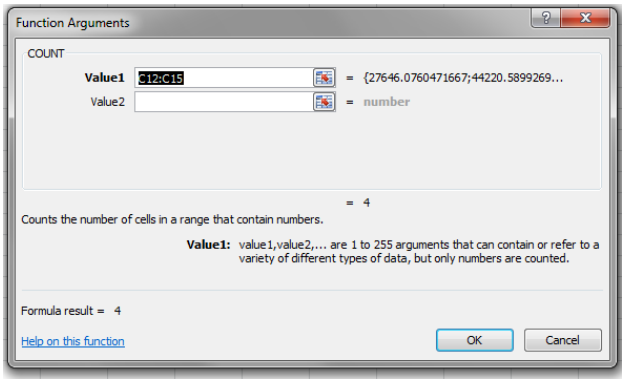
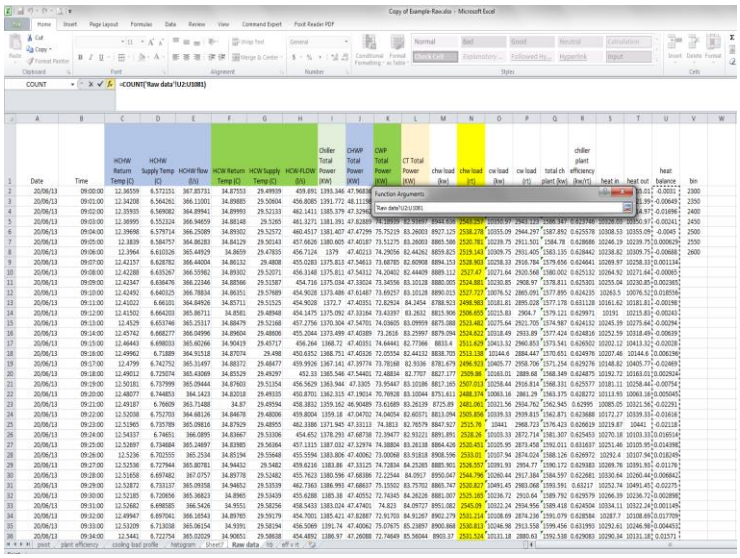


Figure 8.21: *Summary of Performance*

Step 3: Go back to **Raw data**, select the entire column of Heat Balance by using ctrl + shift+⬇ Click **OK**.



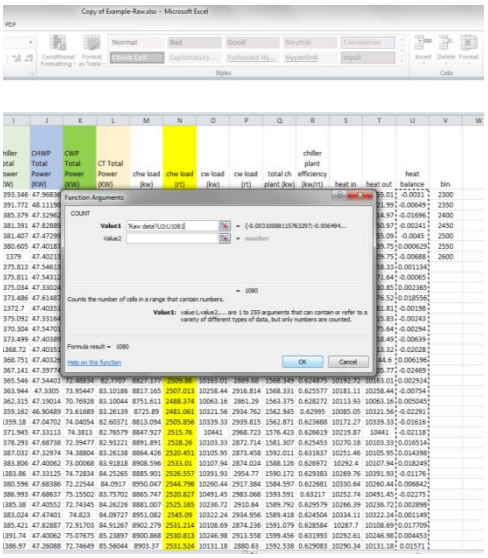
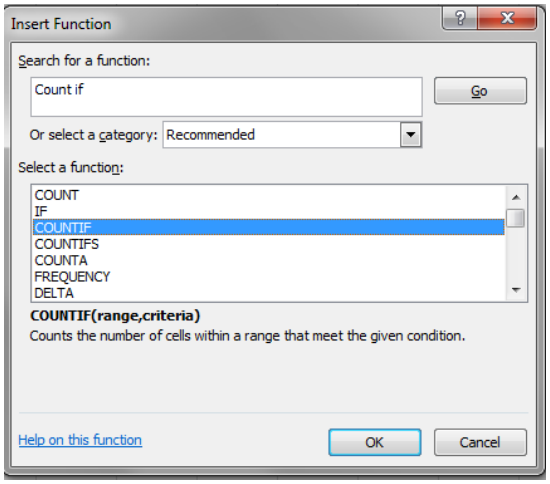
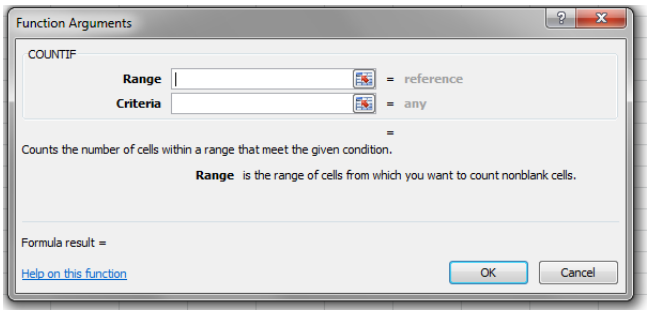


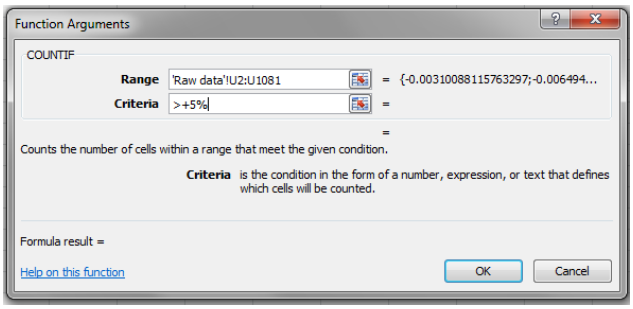
Figure 8.22: *Summary of Performance*

Step 4: To find out the **Data Count > +5% error** (No 11), use the **Count If** function from Fx, click on **Fx**, **Type Count If** at search for a function box, press **Go**, choose **COUNTIF** and Click **OK**.

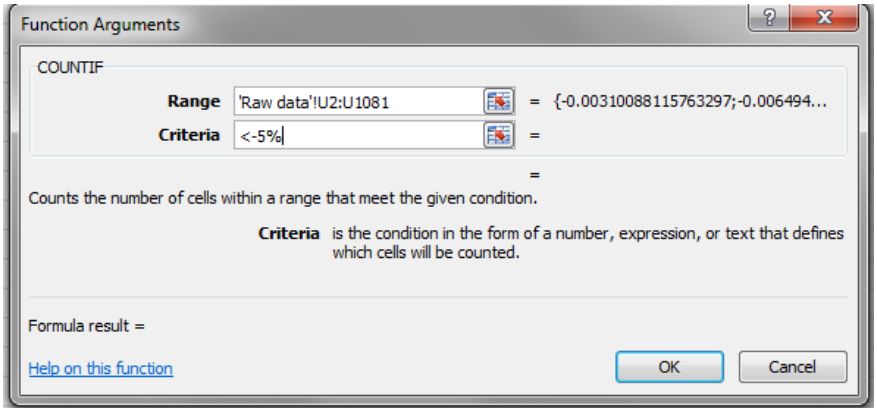


Step 5: Go back to raw data and select the **Heat Balance entire column** as **Range** by using ctrl + shift + , **Type** > +5% at the **Criteria,** Click **OK**.





Step 6: To count the Data Count <-5% Error (No 12), Repeat same steps as (No 11) for COUNTIF function, except that criteria change to <-5%.



9 Safety Considerations

The following measurements are commonly carried out during energy auditing works:

i. Electrical power measurement on primary or secondary circuits.
ii. Non-contact measurement of liquid flow.
iii. Liquid temperature measurement.
iv. Liquid pressure measurement.
v. Air flow measurement.
vi. Air temperature measurement.
vii. Air relative humidity (RH) measurement.
viii. Air pressure measurement.
ix. Carbon Dioxide (CO_2) measurement.
x. Carbon Monoxide (CO) measurement.
xi. Illuminance (Lux) measurement.

To measure the above parameters, relevant sensors are installed at different locations of the plants such as electrical panels, pipes carrying high temperature or pressure fluids, higher elevation, etc. which involve potential risks. Hence, risk analysis for the measurement works should be carried out carefully and effective risk control measures should be implemented to control the potential risks.

Learning Outcomes

Participants will be able to:

i. Acquire basic safety knowledge related to energy auditing works.
ii. Be familiar with risk control options for energy auditing work
iii. Form appropriate risk matrix.
iv. Assess risk for each measurement task
v. Consider risk control measures

9.1 Risk Control Options

The different risk control options are:

Elimination: Elimination of risk refers to the total removal of the hazards. This is a permanent solution and should be attempted in the first instance, if technically and financially feasible.

Substitution: Substitution represents alternative lower risk methods of carrying out jobs. For example: Measure electrical power in secondary circuits instead of primary circuits.

Engineering Controls: Engineering controls refer to physical means that limit the risk. For example: Erect a barrier to interrupt the transmission path of the hazard.

Administrative Controls: Administrative controls represent the development of the procedures or instructions to reduce the risk. Competent persons should conduct the risk assessment. For example: Implementation of permit-to-work systems and scheduling of incompatible works.

Personal Protective Equipment (PPE): PPE is considered as a last resort, after all other control measures have been considered. PPE should be chosen correctly.

9.2 Risk Matrix

A 3 x 3 or 5 x 5 risk matrix can be adopted as shown in Figure 9.1 to analyse the level of risk for each measurement task:

Consequence / Occurrence	**Minor**	**Moderate**	**Major**
Remote	Low	Medium	High
Likely	Medium	High	High
Very Likely	High	High	High

(a) 3 x 3 risk matrix

Consequence / Occurrence	Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
Rare (1)	**1**	**2**	**3**	**4**	**5**
Remote (2)	**2**	**4**	**6**	**8**	**10**
Occasional (3)	**3**	**6**	**9**	**12**	**15**
Frequent (4)	**4**	**8**	**12**	**16**	**20**
Almost Certain (5)	**5**	**10**	**15**	**20**	**25**

(b) 5 x 5 risk matrix

Figure 9.1: *3 x 3 and 5 x 5 risk matrices.*

Definitions of occurrences and consequences for 3x3 risk matrix could be:

Occurrences:

Remote: Not expected to occur but still possible.

Likely: Possible or known to occur.

Very likely: Continual or repeating experience.

Consequences:

Minor: Cuts treated with first aid, superficial injuries

Moderate: Minor illness preventing work < 1 week, Temporary disability < 1 week.

Major: Inpatient hospitalization, Permanent disability, Involves fatality

Definitions of occurrences and consequences for 5x5 risk matrix could be:

Occurrences:

Rare (1): Not expected to occur but still possible

Remote (2): Not likely to occur under normal circumstances

Occasional (3): Possible or known to occur

Frequent (4): Common occurrence

Almost certain (5): Continual or repeated experience

Consequences:

Insignificant (1): Not likely to cause injury

Minor (2): Injury requiring first aid only

Moderate (3): Injury requiring medical treatment or leading to disability

Major (4): Serious injuries or life threatening occupational diseases

Catastrophic (5): Multiple major injuries, fatal disease or involves fatality

Risk levels for the 3x3 or 5x5 risk matrices could be defined as:

Low (1 to 3): No action is required. No additional risk control measures are needed.

Medium (4 to 9): Efforts should be made to reduce the risk. Careful evaluation of hazards should be carried out to make the risk as low as reasonably practical.

High (10 to 15): Action needed to contain the risk to at least medium risk level and management review required before commencing the work. If possible, the hazard should be eliminated before the work progresses.

9.3 Risk Assessment

Potential risks and probable control measures for different measurement activities are discussed in the following sections.

Example 1

Activities for Measurement of Electrical Power: Identify suitable place using single line drawings and/or site inspection for the installation of the electric power meter. Put on Personal Protective Equipment (safety goggles, safety boots etc.). De-energise main breaker of the electrical panel, if possible. Clamp voltage clips on the bus bars or cables. Install clamp-on current transformer on the power cables or bus bars. Perform safety check and energise the main breaker.

Risk Assessment and Control Measures

Activity	Hazard	Occurrence	Consequence	Risk levels	Risk Control Measures
Electrical power measurement	Electric shock	Remote (2)	Catastrophic (5)	High (10)	i. Cordon-off the area ii. De-energise main breaker, if possible. iii. Wear electrical insulating gloves, safety goggles, safety boots, etc. iv. Wear ear plugs in plant rooms v. Work to be carried out by trained engineer. vi. Use earth-leakage circuit breaker (ELCB), if power supply is required. vii. Check to ensure no loose or exposed section on power supply extension cables and electrical tools used

Example 2

Activities for Measurement of Liquid Flow: Identify suitable locations for the installation of flow meters on the external surface of pipe. Mark locations for removal of insulation, if necessary. Clean exterior surface of pipe. Apply grease on transducers of the ultrasonic flow meter and install on the pipe. Connect transducers to flow meter/data logger and connect to the electric power source. Configure the flow meter and data logger and start measuring the flow rate.

Risk Assessment and Control Measures

Activity	Hazard	Occurrence	Consequence	Risk levels	Risk Control Measures
Non-contact measurement of liquid flow	Electric shock, hand cut by sharp edges and fall from high level	Rare (1)	Minor (2)	Low (2)	i. Cordon-off the area ii. Wear safety shoes, safety goggles and safety helmet iii. Wear ear plugs in plant rooms iv. Use ELCB for power supply v. Check electrical tools and cables to ensure no loose or exposed cables & joints vi. Wear safety harness if height > 3m vii. For work between 1 to 3 metres, use a ladder secured to fixed object or secured by another person. Do not use the top two steps.

Example 3

Activities for Measurement of Temperature of High Pressure Pipe Lines: Identify suitable thermowell for the installation of the temperature sensor. Check whether the thermowell is filled with liquid. If not, fill with appropriate liquid. Insert the temperature sensor sufficiently into the thermowell, secure and make good contact. If there is no appropriate thermowell, identify suitable pipe section for hot tapping. Weld pipe of suitable diameter and length vertically on the fluid carrying pipe. Install valve on the other end of the hot tapping pipe. Conduct pressure test to ensure no leakage through the welded joint. Drill the fluid carrying pipe through the hot tapping pipe and close the valve. Insert rubber plug inside the hot tapping pipe. Insert the temperature sensor sufficiently into the fluid through the rubber plug. Connect the temperature sensor to the data logger and configure the data logger.

Risk Assessment and Control Measures

Activity	Hazard	Occurrence	Consequence	Risk levels	Risk Control Measures
Temperature measurement of high pressure pipe lines	Hand cut by sharp edges, hit by high pressure liquid and fall from high level	Occasional (3)	Moderate (3)	Medium (9)	i. Cordon-off the area ii. Wear safety shoes, safety goggles and safety helmet iii. Wear ear plugs in plant rooms iv. Remove existing thermometer from thermowell carefully. v. Wear safety harness if height > 3m vi. For work between 1 to 3 metres, use a ladder secured to fixed object or secured by another person. Do not use the top two steps.

Example 4

Activities for Measurement of Pressure of High Pressure Pipe Lines: Identify suitable locations for the installation of pressure sensor. Close isolation valve and slowly unscrew the existing pressure gauge. Install the new pressure transducer. Carefully open the isolation valve. Connect the pressure sensor to the data logger and configure the data logger.

Risk Assessment and Control Measures

Activity	Hazard	Occurrence	Consequence	Risk levels	Risk Control Measures
Pressure measurement of high pressure pipe lines	Hit by high pressure fluid and fall from high level	Occasional (3)	Moderate (3)	Medium (9)	i. Cordon-off the area ii. Wear safety shoes, safety goggles and safety helmet iii. Wear ear plugs in plant rooms iv. Close isolation valve properly v. Ensure isolating valves are functioning before removal or installation of pressure gauge vi. Wear safety harness if height > 3m vii. For work between 1 to 3 metres, use a ladder secured to fixed object or secured by another person. Do not use the top two steps.

Example 5

Activities for Measurement of Air Flow Rate, Temperature and RH of AHU: Identify suitable locations for measuring the air flow rate, temperature and RH. Switch off the fan of AHU. Ensure the AHU motor is stopped before opening the door of the AHU. Install the temperature and RH sensors carefully at appropriate locations. Close the AHU door and switch on AHU fan. Measure the velocity of incoming air at different locations on the filter of AHU.

Risk Assessment and Control Measures

Activity	Hazard	Occurrence	Consequence	Risk levels	Risk Control Measures
Measurement of air flow rate, temperature and RH	High noise level, moving parts	Occasional (3)	Moderate (3)	Medium (9)	i. Cordon-off the area ii. Wear safety shoes, safety goggles and safety helmet iii. Wear ear plugs iv. Ensure no loose clothing v. Before going inside fan compartment, make sure the fan is turned off. One person to stand near switch to ensure fan is not turned on.

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