MEASUREMENT & VERIFICATION (M&V) GUIDELINES FOR CENTRAL AIR-CONDITIONING PLANT

(Reference: Green Mark for Non-Residential Existing Buildings Version 3)

(1) Instrumentation for Monitoring Central Water Cooled Chilled - Water Plant Efficiency

The instrumentation shall have the capability to calculate resultant chilled water plant efficiency within ± 5 % of the true value and in accordance with ASHRAE Guide 22 and AHRI 550/590. The methodology for determining the total uncertainty of measurement shall be computed using the root-sum square formula as follows:

$$Error_{rms} = \sqrt{\left(\sum (U_N)^2\right)}$$

where U_N = individual uncertainty of variable N (%)

N = mass flow rate, electrical power input or delta T

In deriving the measurement errors contributed by flow meters, an additional 1% is to be included in the computation.

The following instrumentation and installation are also required to be complied with:-

(a) Location and installation of the measuring devices to meet the manufacturer's recommendation.

(b) Data Acquisition system i.e. Analog-to-digital or A/D converter used shall have a minimum resolution of 16 bit. For example,

- The specification for the A/D converter of the BTU meter should have a minimum resolution of 16-bit. This applies to direct data acquisition from the BTU meter.
- For data acquisition using Building Management System (BMS), the specification of the specific Digital Direct Controller (DDC) connecting the temperature sensors should have a minimum resolution of 16-bit.

(c) All data logging with capability to trend at 1 minute sampling time interval.

(d) Flow meters for chilled-water and condenser water loop shall be ultrasonic / full bore magnetic type or equivalent.

(e) Temperature sensors shall have a minimum end-to-end accuracy of ± 0.05 °C over entire measurement / calibration range. All thermo-wells shall be installed in a manner which ensures that the sensors can be in direct contact with fluid flow.

(f) 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.

(g) 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).

(2) Verification of central chilled water plant instrumentation : Heat balance – substantiating test

The verification of chilled water plant instrument using the heat balance - substantiating test shall be in accordance to AHRI 550/590. The heat balance shall be conducted over the entire normal operating hours with more than 80% of the computed heat balance within ± 5% over the audit period.

The heat balance is represented by the following equation:

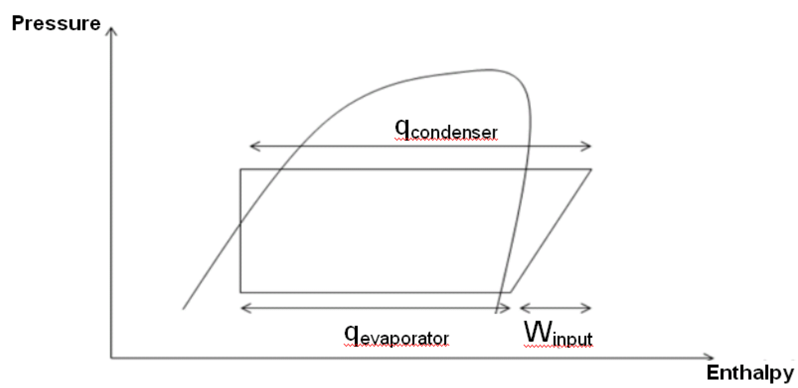
$$q_{condenser} = q_{evaporator} + W_{input}$$

where $q_{condenser}$ = heat rejected

$q_{evaporator}$ = cooling load

W_{input} = measured electrical power input to compressor

The pressure enthalpy diagram below shows the concept of heat balance equation in a vapour compression cycle.



Pressure Enthalpy Diagram

The system heat balance of the chilled water plant shall be computed using the formula stated below over the normal operating hours,

$$\text{Percent Heat Balance} = \frac{(q_{evaporator} + W_{input}) - q_{condenser}}{q_{condenser}} \times 100\% \leq 5\%$$

For open drive chillers, the W_{input} shall take into account the motor efficiency provided by the manufacturer. An example is provided as follows:

Input power (measured)	= 100kW
Motor rated efficiency (η)	= 90%
Adjusted W_{input}	= 100kW x 90%
	= 90kW

Where hydraulic losses of pumps constitute a substantial heat gain, these losses have to be properly accounted for. The value shall be determined from pump efficiency values provided by the manufacturer. An example is illustrated as follows:

(a) **For chilled water pump(s) adjustment,**

Motor input power (measured) = 30kW (A)

Motor rated efficiency (η) = 90% (B)

Pump rated efficiency (η) = 80% (C)

Hydraulic losses = (A) x (B) x [(100% – (C)]

= 30kW x 90% x (100% - 80%)

= 5.4kW

Adjusted W_{input} = kW_i (chillers) + 5.4kW

Where kW_i (chillers) = adjusted power input to compressor, kW

(b) **For condenser water pump(s) adjustment,**

Motor input power (measured) = 20 kW (A)

Motor rated efficiency (η) = 90% (B)

Pump rated efficiency (η) = 80% (C)

Hydraulic losses = (A) x (B) x [(100% – (C)]

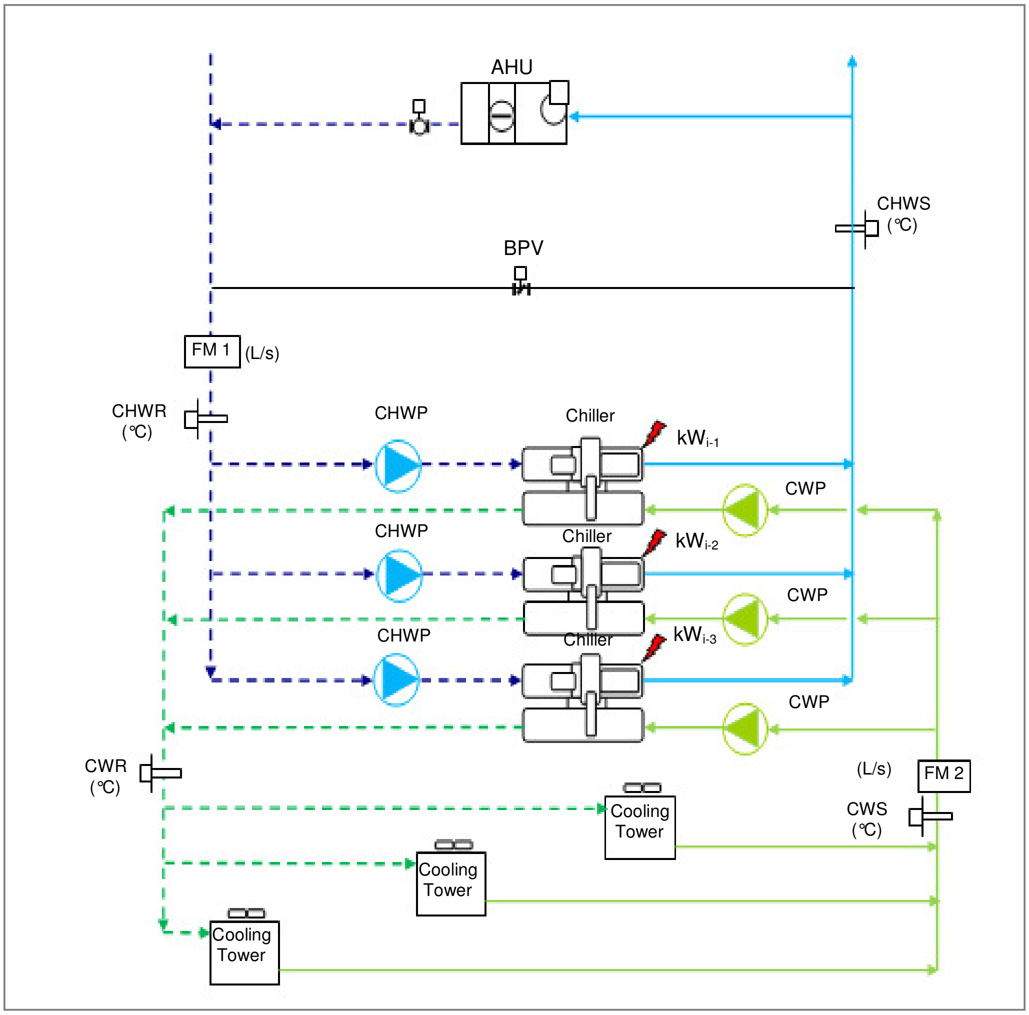
= 20kW x 90% x (100% - 80%)

= 3.6 kW

Adjusted $q_{condenser(adj)}$ = $q_{condenser}$ - 3.6kW

(3) Worked examples - Determining Heat Balance for Different Plant Configuration

(a) Plant A – Constant Primary Chilled-Water System



A: $q_{evaporator}$ = m x Cp x ΔT = FM1 x Cp x (CHWR - CHWS)

B: $q_{condenser}$ = m x Cp x ΔT = FM2 x Cp x (CWR - CWS)

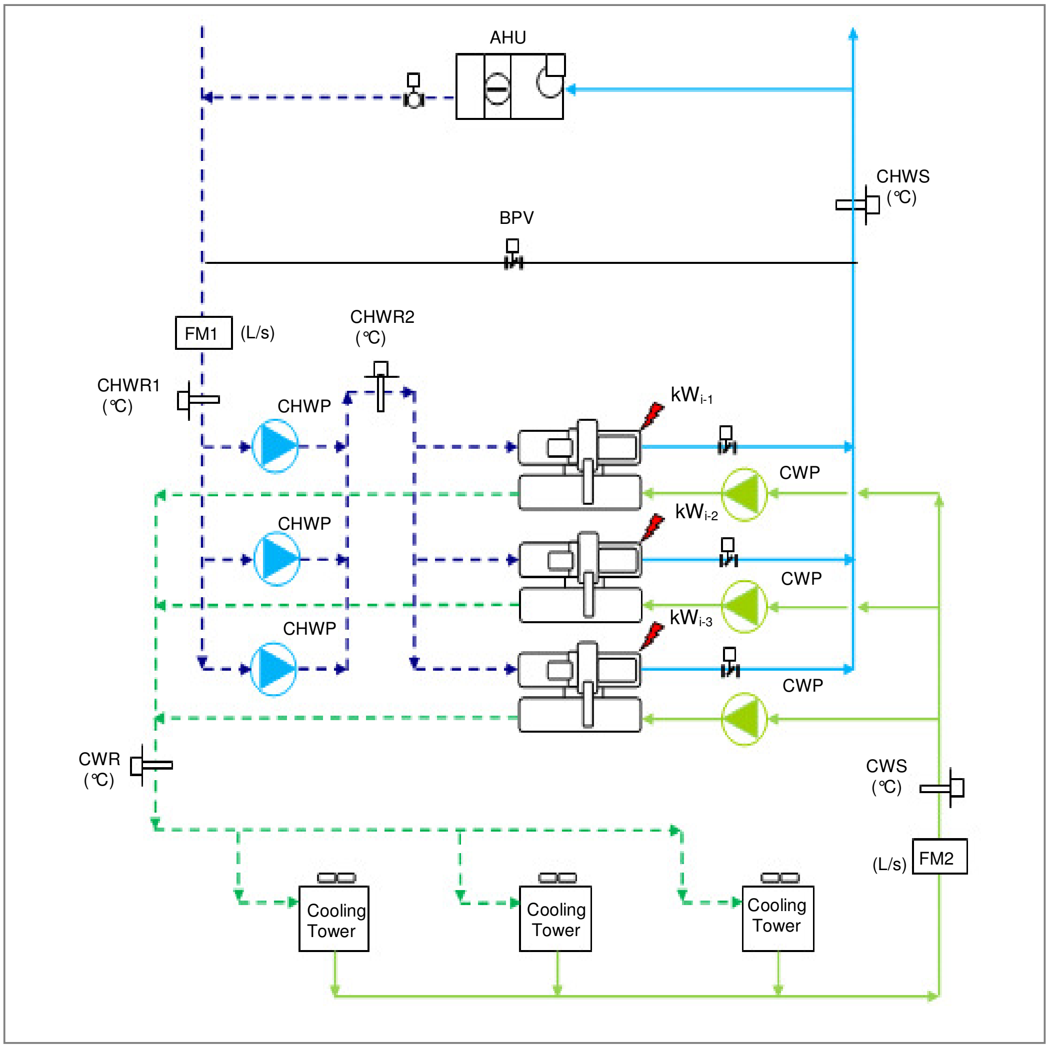
C: W_{input} = $kW_{i\text{-}1} + kWi_{\text{-}2} + kWi_{\text{-}3}$

where Cp = 4.19 kJ/kg.ºC and density of chilled water is assumed to be 1kg/l

Percent heat balance = [(A + C) – B] / B x 100%

Note : Hydraulic losses of pumps constituting substantial heat gain can be included on the right hand side of the heat balance equation. The value of which shall be determined from certified gear losses and pump efficiency values provided by the manufacturer.

(b) Plant B – Variable Primary Chilled-Water System

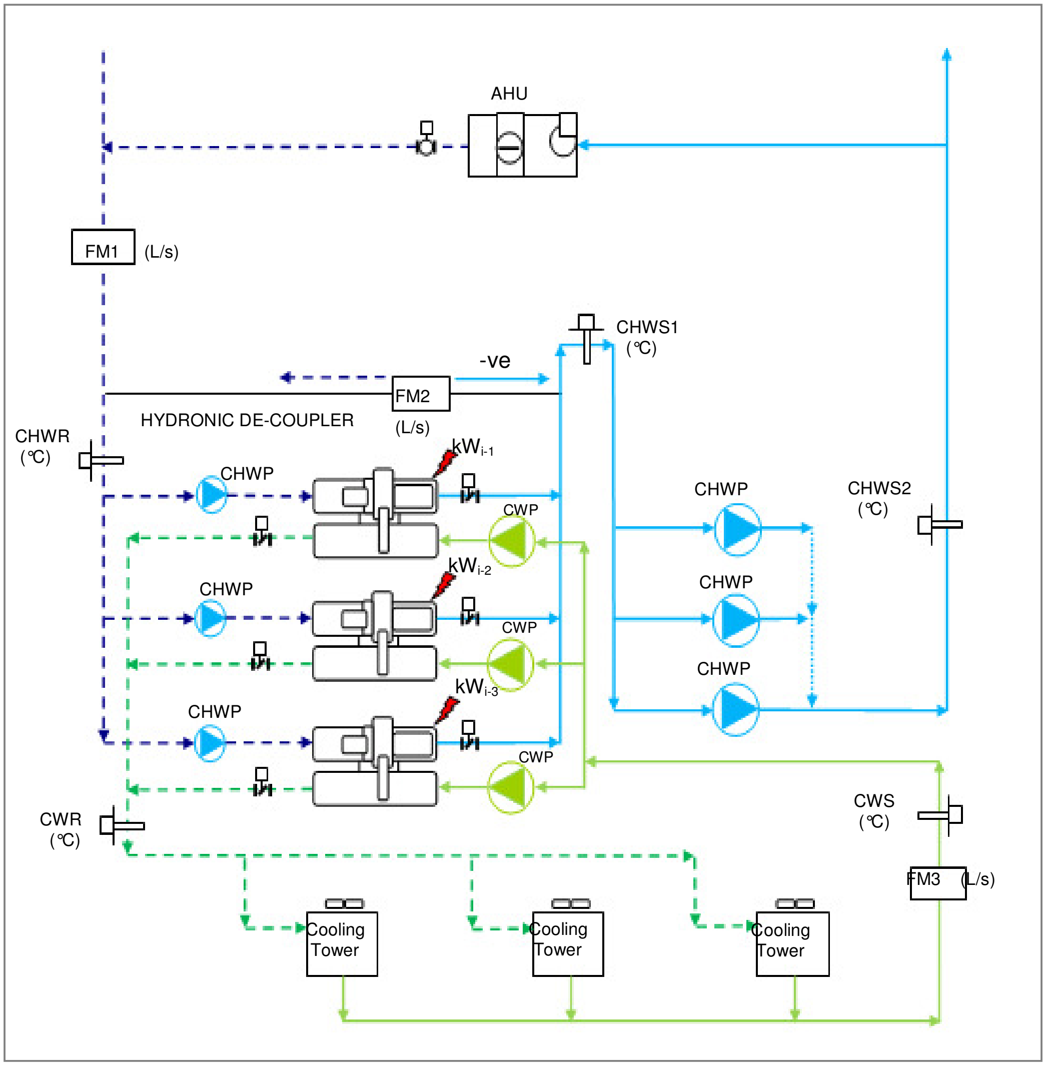


A:	$q_{evaporator}$	= FM1 x Cp x (CHWR2 - CHWS)
B:	$q_{condenser}$	= FM2 x Cp x (CWR - CWS)
C:	W_{input}	= $kW_{i-1} + kWi_{-2} + kWi_{-3}$

Percent heat balance = [(A + C) – B] / B x 100%

Note: In the event where CHWR1 is used and heat balance exceeds ±5%, hydraulic losses of pumps constituting substantial heat gain can be included on the right hand side of the heat balance equation. The value of which shall be determined from certified gear losses and pump efficiency values provided by the manufacturer.

(c) Plant C – Constant Primary & Variable Secondary Chilled-Water System



A: $q_{evaporator}$ = (FM1 + (+/-FM2)) x Cp x (CHWR – CHWS1)

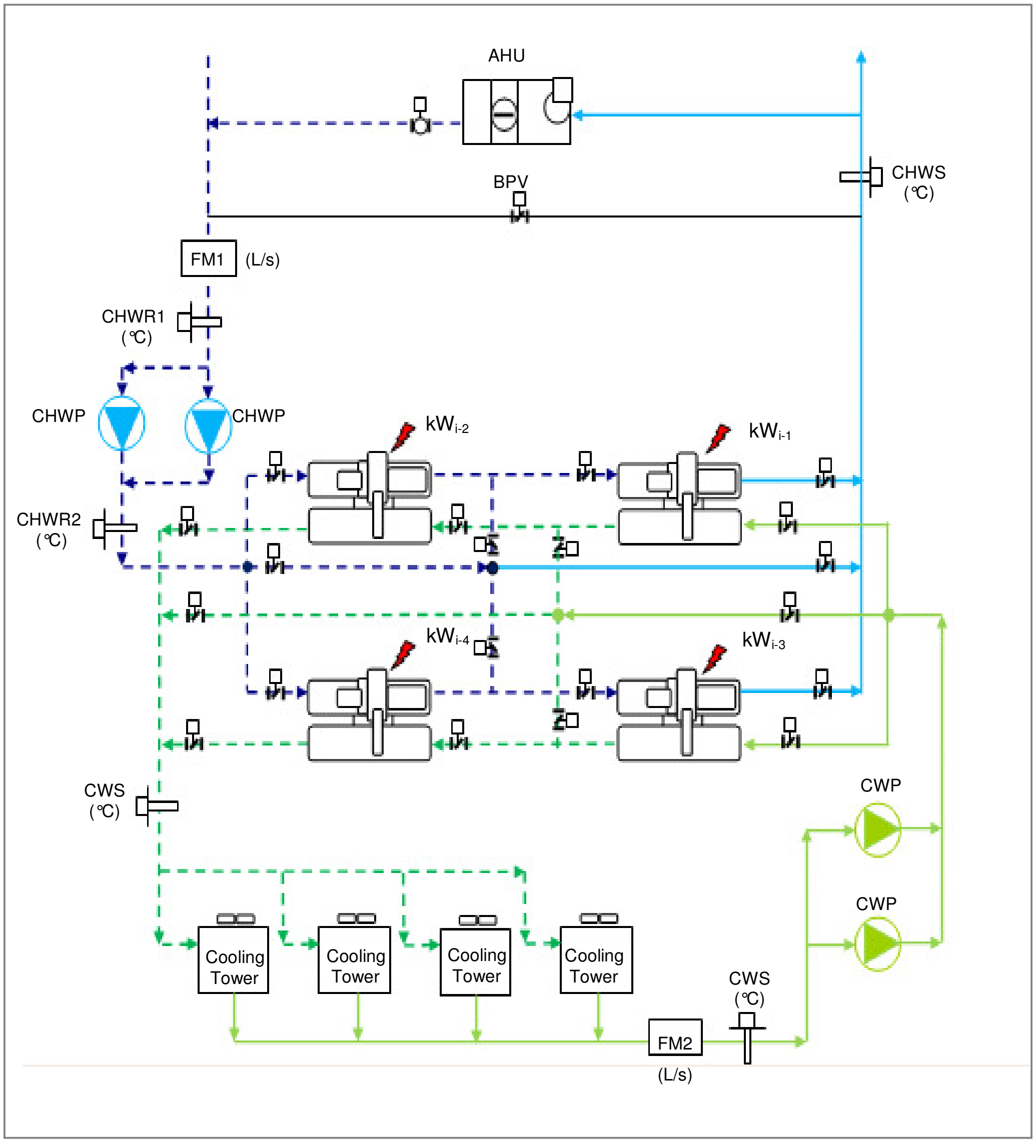
B: $q_{condenser}$ = FM3 x Cp x (CWR - CWS)

C: W_{input} = kW_{i-1} + kW_{i-2} + kW_{i-3}

Percent heat balance = [(A + C) – B] / B x 100%

Note: In the event where hydraulic losses of pumps constitute a substantial heat gain, these losses have to be properly accounted for. The value shall be determined from certified gear losses and pump efficiency values provided by the manufacturer.

(d) Plant D – Series Counter Flow Chilled-Water System



A:	$q_{evaporator}$	= FM1 x Cp x (CHWR2 - CHWS)
B:	$q_{condenser}$	= FM2 x Cp x (CWR - CWS)
C:	W_{input}	= $kW_{i-1} + kWi_{-2} + kWi_{-3} + kWi_{-4}$

Percent heat balance = [(A + C) – B] / B x 100%

Note: In the event where CHWR1 is used and heat balance exceeds ± 5%, hydraulic losses of pumps constituting substantial heat gain can be included on the right hand side of the heat balance equation. The value of which shall be determined from certified gear losses and pump efficiency values provided by the manufacturer.

(5) Heat Balance Calculation

The following example illustrates a successful heat balance where 80% of the computed heat balance falls within ± 5% as required.

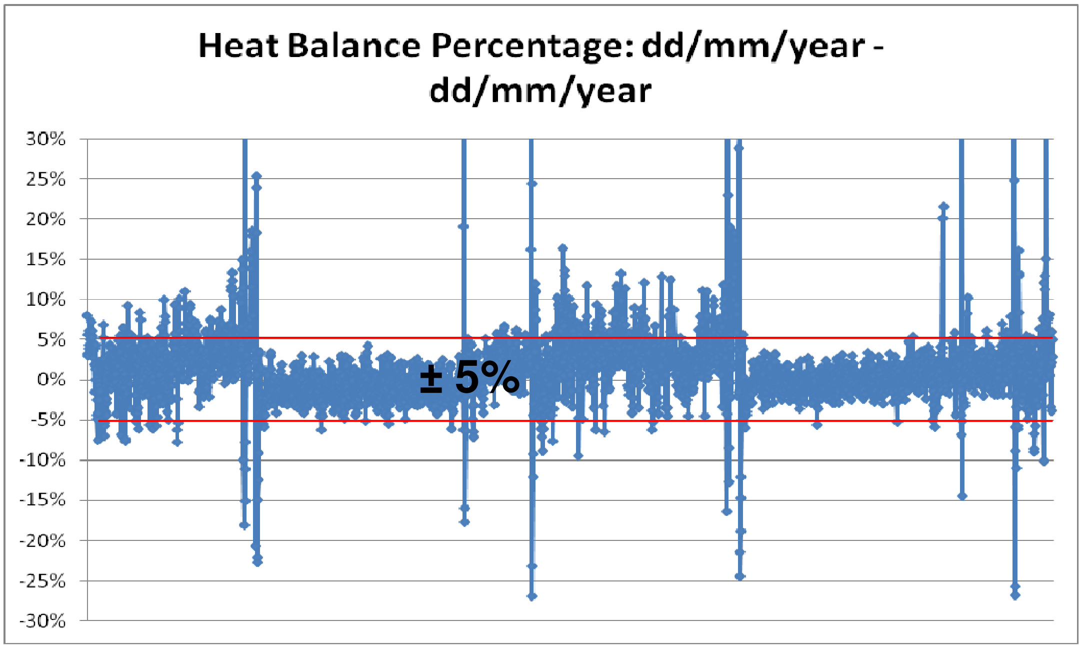
	(a) Chilled water supply temperature	(b) Chilled water return temperature	(c) Chilled water flow rate	(d) Condenser water supply temperature	(e) Condenser water return temperature	(f) Condenser water flow rate	(g) Chiller kWe	(h) Heat Gain	(i) Heat Rejected	(j) Percent Heat Balance
dd/mm/yyyy hh:mm	°C	°C	L/s	°C	°C	L/s	kW	kW	kW	%
16/06/2010 15:00	6.70	12.60	84.10	29.4	35.5	97.65	308	2,079.04	2,495.84	-4.36
16/06/2010 15:01	6.71	12.50	84.20	29.5	35.4	97.60	309	2,042.70	2,412.77	-2.53
16/06/2010 15:02	6.72	12.30	84.30	29.6	35.3	97.55	310	1,970.95	2,329.79	-2.10
16/06/2010 15:03	6.73	12.10	84.20	29.7	35.2	97.50	311	1,894.53	2,246.89	-1.84
16/06/2010 15:04	6.74	12.20	84.10	29.8	35.1	97.55	312	1,923.99	2,166.29	3.22
16/06/2010 15:05	6.75	12.00	84.00	29.9	35	97.60	311	1,847.79	2,085.61	3.51
16/06/2010 15:06	6.74	12.30	84.10	29.8	35.1	97.65	310	1,959.23	2,168.51	4.64
16/06/2010 15:07	6.73	12.10	84.20	29.7	35.2	97.60	309	1,894.53	2,249.19	-2.03
16/06/2010 15:08	6.72	12.10	84.30	29.6	35.3	97.55	308	1,900.31	2,329.79	-5.21
16/06/2010 15:09	6.71	12.20	84.20	29.5	35.4	97.50	309	1,936.86	2,410.30	-6.82
16/06/2010 15:10	6.70	12.40	84.10	29.4	35.2	97.55	310	2,008.56	2,370.66	-2.20
					Percentage of heat balance within ± 5% =					82%

(h) Heat Gain = m x Cp x ΔT = (c) x 4.19kJ/kg.ºC x [(b) – (a)]

(i) Heat Rejected = (f) x 4.19 kJ/kg ºC x [(e) – (d)]

(j) Percentage heat balance = [(g) + (h) – (i)] / (i) x 100%

System level heat balance plot (example)



Summary of Heat Balance (example)

	Quantity	Unit	Formula
Sum of total electrical energy used	6814	kWh	(A)
Sum of total cooling produced	12,202	RTh	(B)
Sum of total heat rejected	14,367	RTh	(C)
Chiller Plant Efficiency	0.56	kW/RT	(A) / (B)
Total Heat Balance Data Count	22	-	(D)
Data Count > 5% error	0	-	(E)
Data Count < 5% error	4	-	(F)
Data Count within ±5% error	18	-	(G) = (D) – (E) – (F)
% Heat Balance within ±5% error	82	%	(G) / (D) x 100%

Based on the above example, 82% of the heat balance calculation falls within ± 5% which fulfills the criterion of 80%.

Note : Actual heat balance shall be conducted over the entire normal operating hours with more than 80% of the computed heat balance within ±5% over one (1) week period.

(7) Documentary evidences to be submitted with the Audit Report

(a) Instruments' calibration certificates from accredited laboratory and factory calibration certificates from manufacturers.

(b) Chiller plant room plan layouts showing the details of the instruments' locations and the types of instrumentation used.

(c) Summary of instruments, standards and measurement accuracy to be presented in the following format and example.

ID	Description	Sensor Type	Measurement/ Calibration range	Measurement Uncertainty (%)	Last Calibration Date
TT01	CHWS Temperature	10K Ω Thermistor	0°C - 40°C	± 0.05°C	10/10/2012
TT02	CHWR Temperature	10K Ω Thermistor	0°C - 40°C	± 0.05°C	10/10/2012
TT03	CWS Temperature	10K Ω Thermistor	0°C - 40°C	± 0.05°C	10/10/2012
TT04	CWR Temperature	10K Ω Thermistor	0°C - 40°C	± 0.05°C	10/10/2012
FM01	CHW Flow	Magnetic Full Bore	30 l/s- 200 l/s	± 0.5%	10/10/2012
FM02	CW Flow	Magnetic Full Bore	30 l/s- 200 l/s	± 0.5%	10/10/2012
kW01	Chiller 1 Power	True RMS, 3 phase	60 – 600 kW	± 0.5%	10/10/2012
kW02	Chiller 2 Power	True RMS, 3 phase	60 – 600 kW	± 0.5%	10/10/2012
kW03	CHW Pump 1 & 2 Power	True RMS, 3 phase	20 – 200 kW	± 0.5%	10/10/2012
kW04	CW Pump 1 & 2 Power	True RMS, 3 phase	20 – 200 kW	± 0.5%	10/10/2012
kW05	CT 1 & 2 Power	True RMS, 3 phase	15 – 150 kW	± 0.5%	10/10/2012

(d) Calculation of the overall uncertainty of measurement of the resultant chiller plant efficiency in kW/RT to be within ± 5 % of the true value based on instrumentation specification / calibration certificates. Refer to example below.

Based on the selected instrumentation and manufacturers' specification /calibration, the individual uncertainties in the measurement of mass flow rate (by flow meter), electrical power input (by power meter) and the temperature difference (by temperature sensors) are as follows:

Item	Description	Measurement Uncertainty (% of reading)
1	Temperature sensors with accuracy of ± 0.05°C	1.79% see note (2)
	Temperature difference (ΔT)	
2	Flow Meter	1% see note (1) + 1% (i.e. 2%)
3	Power measurements see note (3)	± 1%

Note:

(1) An additional 1% to be included in the computation of measurement errors for flow meter

(2) The measurement error (%) for temperature sensors is calculated based on the maximum possible difference for the actual delta T (i.e. ΔT). This maximum possible difference can be assumed to be twice the stated accuracy of the sensor. In this case,

Temperature sensor's measurement uncertainty = ± 0.05℃

Design/ Actual ΔT = 5.6 ℃

Measurement errors for ΔT = (0.05℃ x 2)/ 5.6 ℃

= 0.1 ℃ / 5.6 ℃

= 1.79%

(3) The uncertainty of the power measurement system shall take into consideration of the uncertainties of the power meter and any associated voltage and current transformer.

Based on the above information, the overall uncertainty of measurement is as shown in the following:

$$Error_{rms} = \sqrt{(\sum (U_N)^2)}$$

$$= \sqrt{(1.79^2 + 2^2 + 1^2)}$$

$$= 2.86\%$$

where U_N = individual uncertainty of variable N (%)

N = mass flow rate, electrical power input or delta T

Therefore, the total uncertainty for the calculated chilled-water plant efficiency (kW/RT) is 2.86% which falls within the 5% of the true value.

(8) References

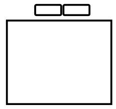
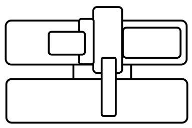
(a) ASHRAE Guideline 22 – Instrumentation for Monitoring Central Chilled-Water Plant Efficiency

(b) AHRI Standard 550/590 – Performance Rating of Water- Chilling Packages Using The Vapor Compression Cycle

Abbreviations used in Worked Examples

CH	Chiller	--
CHWP	Chilled Water Pump	-
CWP	Condenser Water Pump	-
CT	Cooling Tower	-
CHWS	Chilled Water Supply Temperature	ºC
CHWR	Chilled Water Return Temperature	ºC
CHWLR	Chilled Water Load Return Temperature	ºC
CWS	Condenser Water Supply Temperature	ºC
CWR	Condenser Water Return Temperature	ºC
KW	Electrical Power Consumption	kW
KW/RT	Electrical Input kW per Refrigeration Tonnage	I kW/ton
$q_{evaporator}$	Cooling Load	kW or RT
$q_{condenser}$	Heat Rejection	kW or RT
W_{input}	Energy Balance	-
MV	Motorized Valve	-
AHU	Air Handling Unit	
BP	Bypass Line	
BPV	Bypass Valve (2-Way Modulating)	
Cp	Specific Heat Capacity of Water	4.19 kJ/kg.ºC
CCV	Cooling Coil Valve	
ºC	Degrees Celsius	
l/s	Liters per second	
kW	Kilo-Watts	
RT	Refrigeration Ton	
ΔT	Temperature difference, Delta T	

Symbols used in Worked Examples

	CT
	CWP
	CHWP
	CH
	CWS
	CWR
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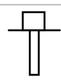
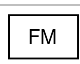
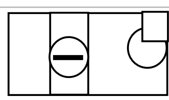
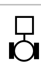
	Water Immersion Sensor
	Flow Meter
	AHU
	CCV (2-Way Modulating)