Seminar 21

Uncertainties in Compressor Performance and Field Performance of Liquid-Chilling Systems

An introduction to field testing of liquid chillers and ASHRAE Standard 184

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Learning Objectives

- Understand the challenges to conducting a field performance test of a liquid chiller compared to a manufacturer's test at the factory.
- Understand the purpose & scope of ASHRAE Standard 184.
- Understand the key features of the ASHRAE Standard 184 Workbook.

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Acknowledgements

Past and present members of ASHRAE SPC-184.

The University of Maryland Facilities Department for the Beta test site for the Uncertainty Calculation Spreadsheet.

Outline/Agenda

- Purpose of ASHRAE Standard-184.
- Scope of ASHRAE Standard-184.
- What measurements are required for a test.
- Challenges of field-testing liquid chillers.
- Combining measurements to characterize chiller performance.
- Introducing the ASHRAE Standard-184 workbook.

Purpose of ASHRAE Standard-184

- The industry has published standards that address factory performance testing of liquid chillers.
  - ASHRAE 30 / AHRI 550/590 (electric) or 560 (absorption) covers many common chiller configurations.
  - If new equipment performance verification is desired, then a factory test can be performed under controlled conditions.
  - Covers the majority of chillers sold, but not all.
- The industry did **not have** a published standard that addresses the field performance testing of liquid chillers.
  - In most cases it is not possible to apply a factory testing standard to field installations where instrument accuracies and installation locations may not be optimal.
- ASHRAE 184, first published in 2016
  - Covers field performance testing.

Scope of ASHRAE Standard-184

This standard includes the following:

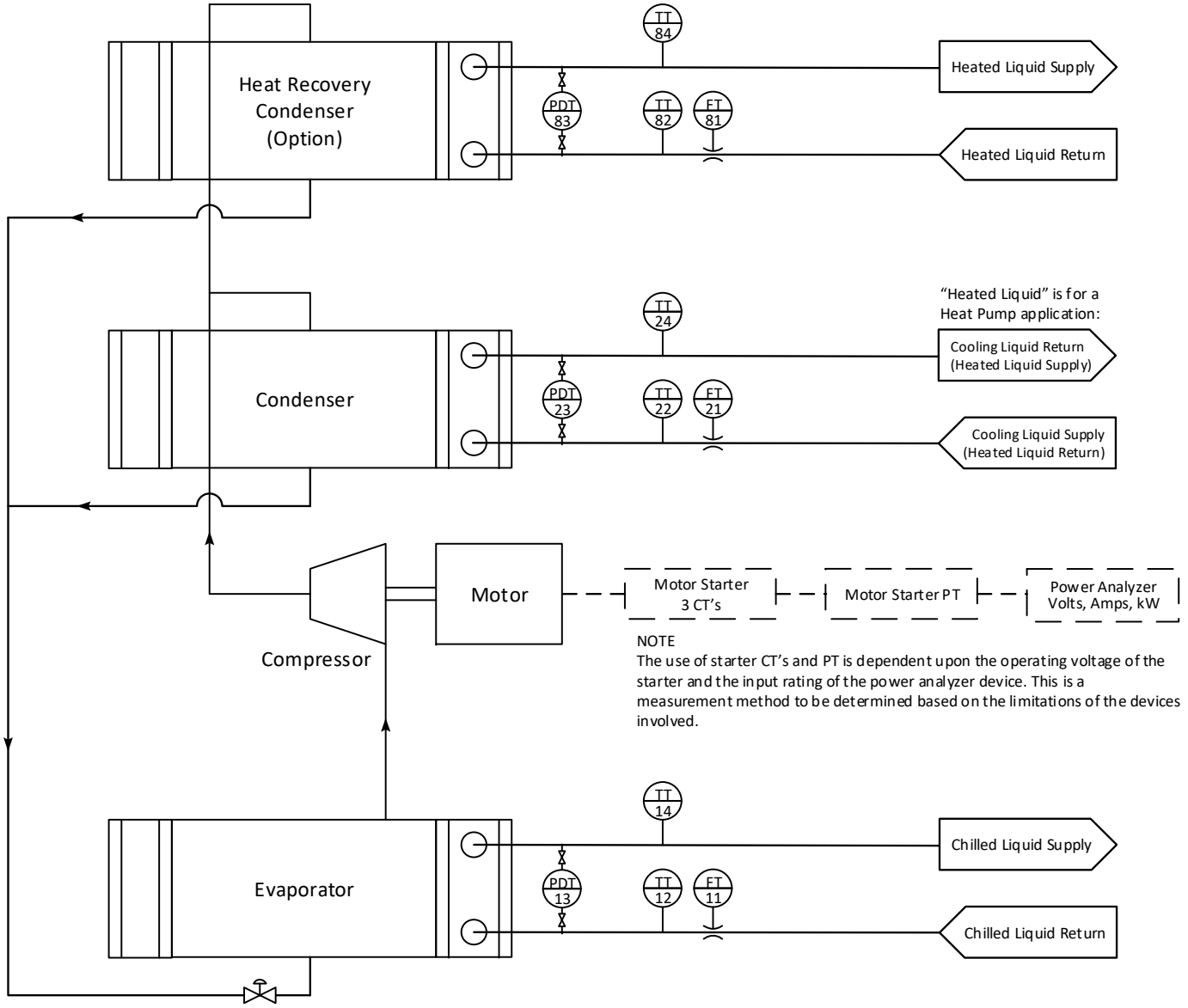
- Types of liquid-chilling systems.
  - Vapor compression cycle.
  - Absorption cycle.
  - Water cooled, air cooled, heat recovery, etc
  - Chillers that cannot be factory tested.
- Any energy source
  - Electricity
  - Steam / hot water
  - Gas
  - Waste heat
- Does not include systems with a net refrigeration capacity less than 10 tonR [35 kW].

Scope of ASHRAE Standard-184

- This standard **does not include a specification of standardized test conditions** under which the liquid-chilling system must operate.
  - Test conditions typically reflect the expected operating conditions and **are customer specified**.
  - They maybe the original design conditions but don't have to be.
- Plant can be in any condition:
  - Any chilled water temperature, design or otherwise
  - Any cooling water / ambient temperature, design or otherwise
  - Any percentage load,
  - Clean or fouled heat exchangers,
  - etc..
- For an effective test the chiller operation should be "stable".

What measurements might need to be taken?

Example:
Water cooled electrically powered Chiller (with the optional heat recovery)



What measurements might need to be taken?

ID / Tag #	Description of Measurement
FT-11	Evaporator liquid flow
TT-12	Evaporator inlet temperature
PDT-13	Evaporator pressure difference
TT-14	Evaporator outlet temperature
FT-21	Condenser liquid flow
TT-22	Condenser inlet temperature
PDT-23	Condenser pressure difference
TT-24	Condenser outlet temperature
No ID	Power consumption for the Chiller, including any auxiliary systems included in the test boundary and includes voltage balance measurement.
	If heat recovery is included:
FT-81	Heat recovery condenser liquid flow
TT-82	Heat recovery condenser inlet temperature
PDT-83	Heat recovery condenser difference
TT-84	Heat recovery condenser outlet temperature

Challenges of field-testing liquid chillers.

- Performance measurement requires measuring several parameters and combining these
  - Capacity result; kW_R, tonR, Btu/hr, etc.
  - Performance result; COP, kW/tonR, EER, etc.
- **Nothing about measurement is certain**….
  - Need to characterize uncertainty
  - eg 932 ± 5.2 kW_R, 1,050 ± 32.4 tonR, 5.21 ± 0.45 COP.
- Two basic types of uncertainty
  - Random
  - Systematic

Challenges of field-testing liquid chillers.

- Random is the variation in the actual measurement
  - "Real" variation in the measured values
  - Plant operational stability

This is what it is….
Can only try to stabilize operation during testing

- Systematic is the accuracy of the measuring system / devices
  - Calibration accuracy of the device
  - Device accuracy
    - Eg 0.2%
  - A to D resolution of the data logger
  - Non-ideally installed device
    - Flow transmitter not installed with required up and downstream straight lengths. Workbook provides some assistance here…
    - Temperature stratification leaving an evaporator

The most challenging characterizations to determine.

Combining measurements to develop a conclusion.

COP derived from (for example)

$$COP = \frac{\text{Gross evaporator capacity}}{\text{Total input power}}$$

$$= \frac{m.c_p.\Delta T + m.\Delta P/\rho}{\sum W}$$

But mass flow is not typically measured directly, volume flow is:

$$= \frac{V.\rho.\ c_p.\Delta T + V.\Delta P}{\sum W}$$

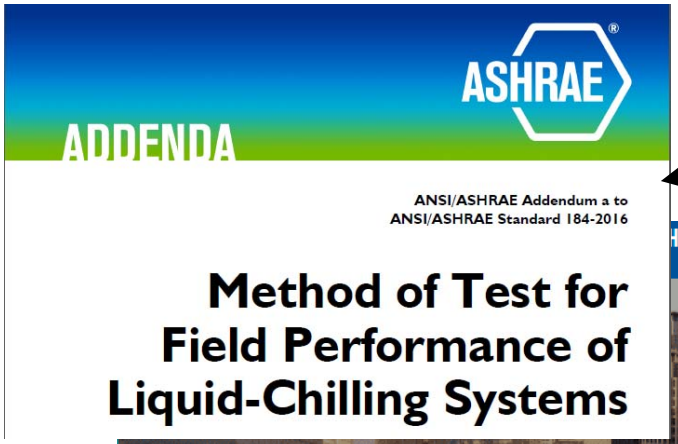
There might be more than one power source…
Even measuring power usually involves current transformers.

- All measurement devices involve uncertainty
  - Don't forget this extends to the recording device / data-logger which is itself has a discrete accuracy:
    - Analog to Digital eg 12 bit = $1/2^{12} = 1/4096 = 0.00024$.

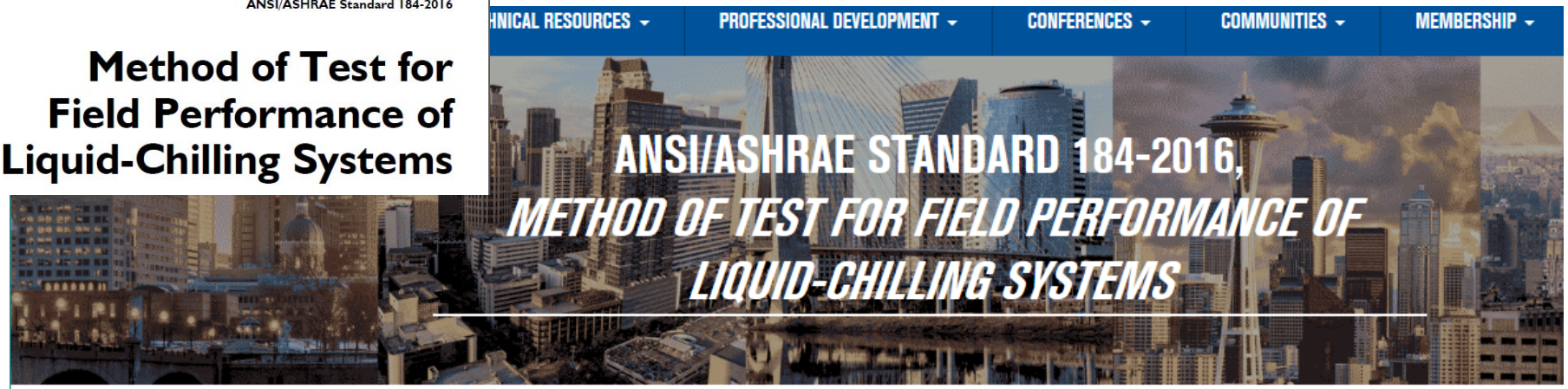
Introducing the ASHRAE Standard-184 workbook.

- The mathematics behind calculating uncertainty can be challenging.
- In support of ASHRAE Standard 184 a workbook has been developed.
  - Published with Addendum A December 7 2018
- Aim is to provide an accessible working calculation of the methods included in the standard.
  - Leads the user through the required steps.
  - Provides an auditable workbook of the calculations.
- User selectable systems and configurations.
- Includes the pre-test estimates
  - Establish agreement of expected outcome prior to testing.

Introducing the ASHRAE Standard-184 workbook.



Addendum a contains link to files



Supplemental Files

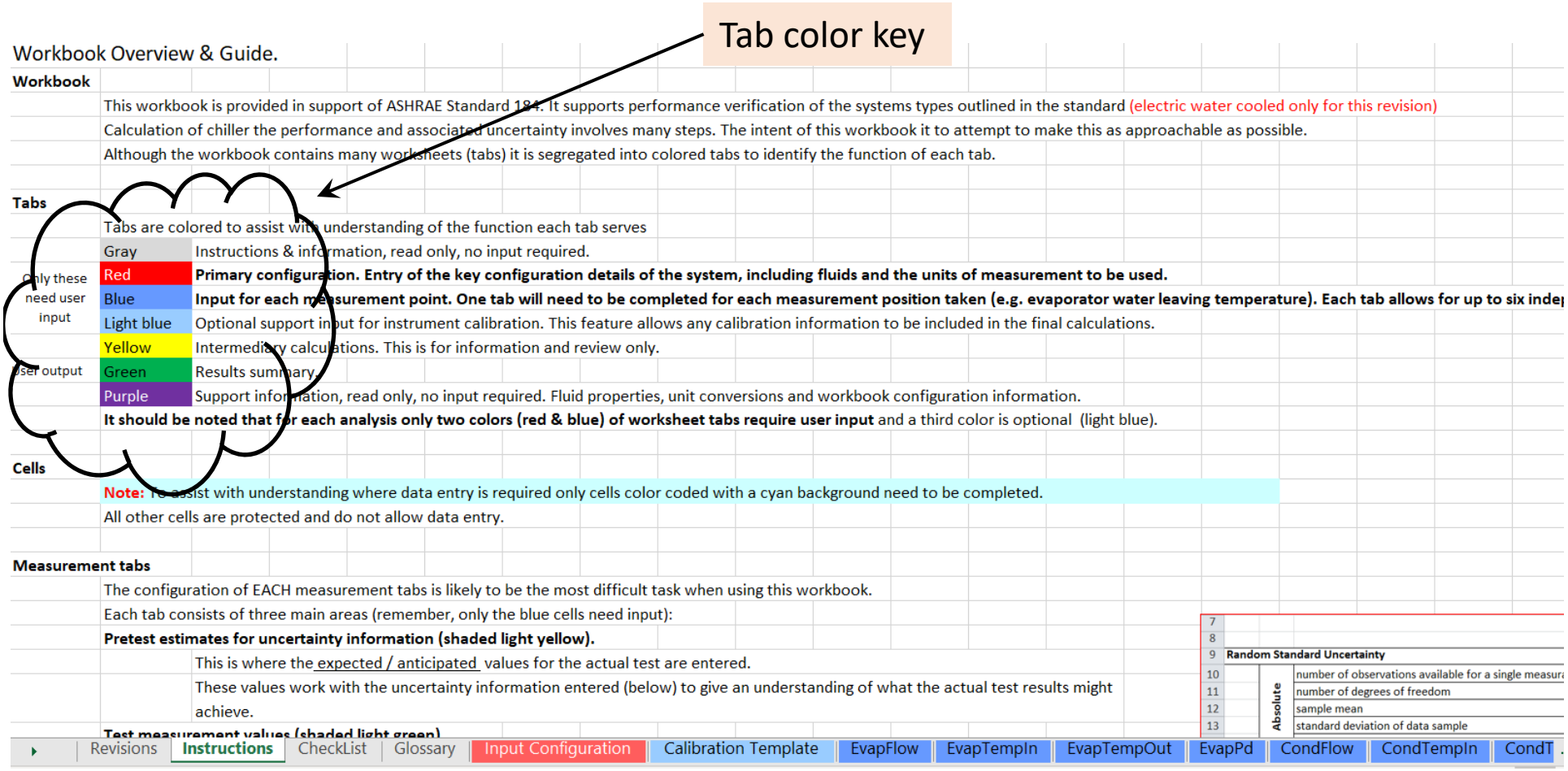
Example Spreadsheet Workbook for Uncertainty Analysis (Informative Appendix I) and Examples of Evaluating Instrument Uncertainty (Informative Appendix J)

- ASHRAE Standard 184 Workbook Sample Data
- ASHRAE Standard 184 Workbook Template
- Instruments—Uncertainty Examples

Files:

- An empty workbook / template
- An example calculation
- Instruments - Uncertainty examples

Workbook - Overview



Workbook – Input Configuration Tab

Set the system & testing Parameters

(ERW) Electric water cooled
(SRW) Steam water cooled
(GRW) Gas engine water cooled
(HAW) Hot water absorption water cooled
(SAW) Steam absorption water cooled
(GAW) Gas absorption water cooled
(ERA) Electric air cooled

This sets the visible tabs ☺

This tab first!

General	
Date of Test	19-Mar-2015
Unit Identification	123456789-0000
Remark 1	This is remark 1
Remark 2	This is remark 2
Remark 3	This is remark 3
Site Owner	
Testing agent	
Job Name	Worksheet Development
Uncertainty Confidence Level	95%
System Type	(ERW) Electric water cooled
Operating Mode	Cooling

Instrumentation	
Type of Flow Measurements	
Evaporator Liquid Flow	Volume
Condenser Liquid Flow	Volume
Hot Water	Volume
Steam	Volume
Gas (Fuel)	Volume
Input Power Measurements	
Number of Electrical Measurements	2

Units of Measurement		
Input	Temperature	°F
	Length	ft
	Pressure	psig
	Pressure Differential	ftH2O(at60°F)
	Volume Flow Rate	gal/min
	Mass Flow Rate	lbm/s
	Power	kW
	Cooling capacity	tonR
	Heating capacity	tonR
	Density	lbm/ft³
	Specific Heat Capacity	Btu/(lbm·Δ°F)
Output	Cooling efficiency	kW/tonR
	Heating efficiency	COP

Fluid Properties		
	Evaporator (cold) Fluid	AHRI water properties
	Condenser (hot) Fluid	AHRI water properties

Set the units of measurement & flow measurement type

Includes water properties
Allows for input of other fluids

Workbook – Measurement Tabs

One tab per measurement position

Only blue cells require input ☺

Random uncertainties captured here

X = EvapFlow
Type Volume Flow Rate
Units gal/min

This measurement worksheet allows test setups ranging from a sin
to six redundant measurement instruments that are averaged into

					Pre-Test Estimates	Test Measurement Values					
						Instrument Number $i = 1 \text{ to } n$					
Random Standard Uncertainty		**Estimate ISO Type**	**symbol**	**units**		1	2	3	4	5	6
Absolute	number of observations available for a single measurand (sample size)		N	-	100	333	0	0	0	0	0
	number of degrees of freedom		ν_s	-	99	332					
	sample mean		$\overline{X}$	gal/min	10800.0	10835.9					
	standard deviation of data sample		s_X	gal/min	108.0	60.9					
	random standard uncertainty of the mean of N observations of a measurand	Type A	$s_{\overline{x}}$	gal/min	**10.80**	**3.34**					
Relative	relative standard deviation		$\frac{s_X}{\overline{X}}$	-	1.00%	0.56%					
	relative random standard uncertainty		$\frac{s_{\overline{x}}}{\overline{X}}$	-	0.10%	0.03%					

					Pre-Test Estimates	Test Measurement Values					
Systematic Standard Uncertainty						Instrument Number $i = 1 \text{ to } n$					
	enter estimated systematic limits of error (expanded systematic uncertainty)	**Distribution Type**	**Estimate ISO Type**	**Relative Variability**							
	Description				**units**	1					
Expanded	calibration residual error (bias error); if available use the expanded standard error of	Normal	Type A	Low	gal/min	108.00	108.00					
	environmental influence (ambient temperature & pressure & humidity, analog signal	Uniform	Type B	Medium	gal/min	27.00	27.00					
	spatial location or installation effect of measurement device (add specific examples fo	Triangular	Type B	Low	gal/min	500.00	300.00					
	resolution	Uniform	Type A	Low	gal/min	0.25	0.21					
	stability versus time (drift), depends on length of time since last calibration	Triangular	Type B	Medium	gal/min	14.00	14.00					
	other *[enter another source of systematic uncertainty]*			High	gal/min							

Estimation of systematic uncertainties

- Provides worked examples of how to convert & combine instrument “accuracies”
- Includes suggestions for non-ideal flow installations

Pre-test

Test – up to 6 points

Workbook – Measurement Tabs

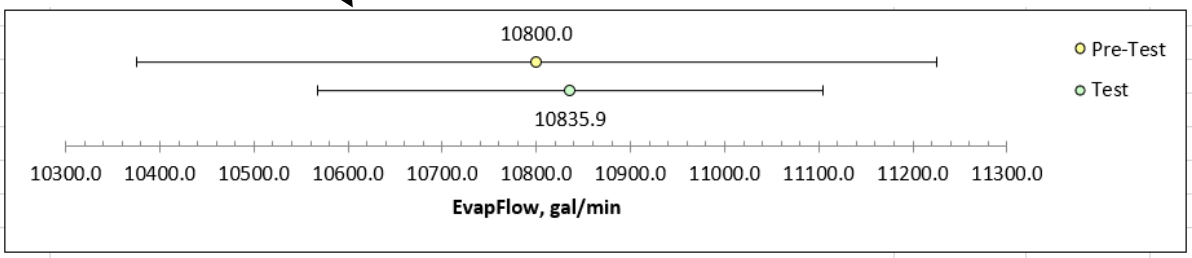
Paste test data, up to 6 instruments

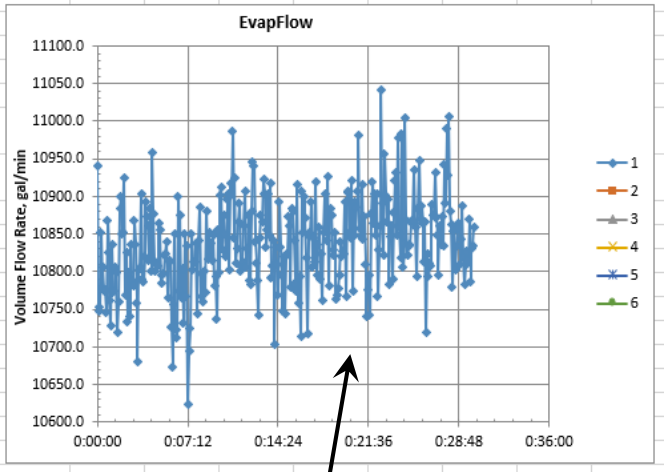
Estimate of A to D resolution

		Instrument Number					
sample number (j)	time	1	2	3	4	5	6
1	0:00:00	10941.1	#N/A	#N/A	#N/A	#N/A	#N/A
2	0:00:06	10753.7					
3	0:00:11	10747.4					
4	0:00:16	10851.7					
5	0:00:22	10780					
6	0:00:27	10805.7					
7	0:00:33	10774.3					
8	0:00:38	10775.8					
9	0:00:43	10745.7					
10	0:00:49	10867.2					
11	0:00:54	10825.8					
12	0:00:59	10761.3					
13	0:01:05	10728.3					
14	0:01:10	10835.3					
15	0:01:15	10773.2					
16	0:01:20	10773.7					
17	0:01:26	10805.3					
18	0:01:31	10798.1					
19	0:01:36	10718.7					
20	0:01:42	10759.8					
21	0:01:47	10884.1					
22	0:01:52	10899.1					
23	0:01:58	10850.6					
24	0:02:03	10852.3					
25	0:02:08	10924					

Estimate of the resolution from the trend log data					
1	2	3	4	5	6
0.21	#N/A	#N/A	#N/A	#N/A	#N/A

Pre-test and Test visualization of sample mean and associated uncertainty





Visualization of test data

Workbook – Interim Results Tabs

Inputs		Pre-Test								Test					
	$i = 1 \text{ to } I$	1	2	3	4	5	6	7	8	1	2	3	4	5	6
Description		Evap liquid volume flow rate	Evap liquid density at flow meter	unused	unused	unused	unused	unused	unused	Evap liquid volume flow rate	Evap liquid density at flow meter	unused	unused	unused	unused
Symbol	-	V_ev	ρ_ev_in							V_ev	ρ_ev_in				
Units	-	gal/min	lbm/ft³							gal/min	lbm/ft³				
Nominal value	$\bar{X}_i$	10800	62.4147867							10835.9064	62.4156516				
Degrees of Freedom, Systematic Uncertainty	$(\upsilon_b)_i$	57.6630254	50							70.7906834	50				
Degrees of Freedom, Random Uncertainty	$(\upsilon_s)_i$	99	99							332	332				
Effective Degrees of Freedom	$(\upsilon_R)_i$	57.963056	50.0000015							70.8774121	50.0000004				
Absolute Systematic Standard Uncertainty	$b_{\bar{X}_i}$	211.797909	0.31207393							134.876541	0.31207826				
Absolute Random Standard Uncertainty	$s_{\bar{X}_i}$	10.8	3.8214E-05							3.33781736	1.8916E-05				
Absolute Combined Standard Uncertainty	$u_{\bar{X}_i}$	212.073087	0.31207394							134.917836	0.31207826				
Sensitivity Coefficient	θ_i	8.34364336	1443.75							8.34375898	1448.54999				
Systematic Standard Uncertainty Contribution to the Combined Uncertainty of	$(\theta_i \cdot b_{\bar{X}_i})^2$	3122876.43	203001.377							1266474.18	204359.109				
Random Standard Uncertainty Contribution to the Combined Uncertainty of the Result	$(\theta_i \cdot s_{\bar{X}_i})^2$	8120.05509	0.00304389							775.619357	0.00075077				
Relative Systematic Contribution to the Standard Uncertainty of the Result	-	93.67%	6.09%							86.06%	13.89%				
Relative Random Contribution to the Standard Uncertainty of the Result	-	0.24%	0.00%							0.05%	0.00%				

Results for Pre-test and Test

Units for Conversion			
	Unit Numerator	gal	lbm
	Unit Denominator	min	ft³

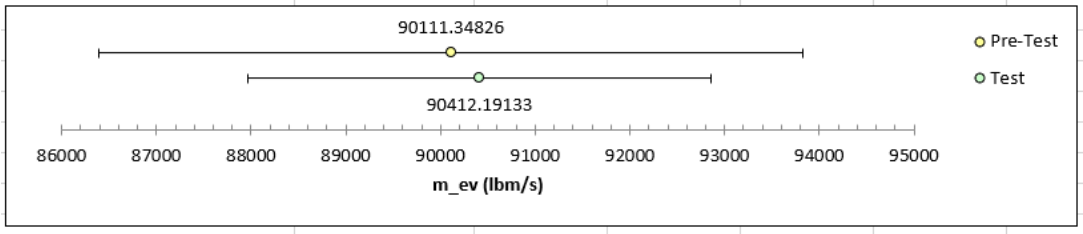
Unit Conversion Calculation

Mass	Length	Time	Temperature	Temperature Difference	Volume	Volume Flow Rate	Mass Flow Rate	Energy	Specific Energy	Power	Density	Specific Heat Capacity	HHV	Force	Pressure
1	1	1	1	1	0.13368056	1	1	1	1	1	1	1	1	1	
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

Mass	Length	Time	Temperature	Temperature Difference	Volume	Volume Flow Rate	Mass Flow Rate	Energy	Specific Energy	Power	Density	Specific Heat Capacity	HHV	Force	Pressure

... EvapPd | CondFlow | CondTempIn | CondTempOut | CondPd | PowerInput1 | PowerInput2 | Result_EvapMassFlowRate | Result_EvapTavg | Result_EvapΔT | Result_EvapNetCapacity ...

Pre-test and Test visualization



Interim results tabs

Workbook – Final Results Tabs

Job Name	Worksheet Development
Unit Identification	123456789-0000
Date of test	1-Jan-2019
Starting Time of Test	12:00:00 AM
Test Duration	30 minutes
System Type	(ERW) Electric water cooled
Remark 1	This is remark 1
Remark 2	This is remark 2
Remark 3	This is remark 3
Number of Measurement Data Points	Between 333 and 333 points

Alternate Summary Results View

System Performance Summary

Evaporator

Evaporator Type	Flooded						
		Test			Pre-Test		
	Units of Measure	Average Value	Uncertainty Value	Relative Uncertainty	Average Value	Uncertainty Value	Relative Uncertainty
Entering Fluid Temperature	°F	52.77	±0.24	±0.023%	53.00	±0.24	±0.023%
Leaving Fluid Temperature	°F	42.01	±0.24	±0.023%	42.00	±0.24	±0.023%
Fluid Temperature Difference	Δ°F	10.76	±0.33	±3.1%	11.00	±0.33	±3.0%
Fluid Flow	gal/min	10840	±270	±1.2%	10800	±420	±2.0%
Net Capacity	tonR	292500	±12000	±4.2%	298000	±16000	±5.2%

Condenser

Condenser Type	Water Cooled						
		Test			Pre-Test		
	Units of Measure	Average Value	Uncertainty Value	Relative Uncertainty	Average Value	Uncertainty Value	Relative Uncertainty
Entering Fluid Temperature	°F	85.65	±0.24	±0.021%	85.00	±0.24	±0.022%
Leaving Fluid Temperature	°F	94.55	±0.24	±0.021%	94.24	±0.24	±0.021%
Fluid Temperature Difference	Δ°F	8.91	±0.33	±3.7%	9.24	±0.34	±3.7%
Fluid Flow	gal/min	15110	±370	±1.1%	15250	±290	±0.89%
Net Capacity	tonR	334800	±16000	±4.7%	350800	±15000	±4.3%

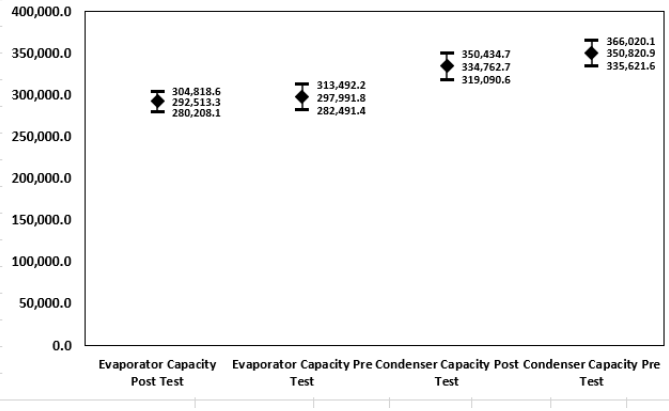
Summary for Pre-test and Test

Driver

Driver Type	Electric Motor			
	Units of Measure	Average Test Value	Uncertainty Value	Relative Uncertainty
Energy Output	kW			
Chiller Total Input Power	kW	2906	±22	±0.74%

Summary of Test Results

	Units of Measure	Average Test Value	Uncertainty Value	Relative Uncertainty
Evaporator Net Capacity	tonR	292500	±12000	±4.2%
Condenser Net Capacity	tonR	334800	±16000	±4.7%
Chiller Total Input Power	kW	2906	±22	±0.74%
Cooling Energy Efficiency	kW/tonR	0.009934	±0.00043	±4.3%
Heating Energy Efficiency	COP	405.1	±22	±5.4%
Evaporator Gross Capacity	tonR	293200	±12000	±4.3%
Condenser Gross Capacity	tonR	333700	±16000	±4.8%
Refrigerant Work Input	kW	2906	±22	±0.74%
Energy Balance	%	-12.6%	±6.4%	±-51%



Typically:

- Evaporator
- Condenser
- Input power
- Heat balance

…and the performance summary

Conclusion

- Field performance testing of chiller cannot be defined like factory chiller testing since the test environment is not controlled.
- ASHRAE Standard 184 covers field performance testing of chillers along with provision for the related influences & issues.
- Standard 184 now includes a workbook to embody the methods and testing covered in the standard.
  - Currently covers water cooled electrically powered chillers.
  - Other types to follow….
- Reminder: It is necessary to identify the objectives between all parties prior to conducting any measurements.
  - Embodied in the Pre-Test calculation.

Bibliography

- ASHRAE Standard 184, Method of Test for Field Performance of Liquid Chilling Systems

Questions?

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