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.
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)

- Evaporator
- Motor
- Compressor
- Condenser
- Heat Recovery Condenser (Option)
- Heated Liquid Supply
- Heated Liquid Return
- Cooling Liquid Supply (Heated Liquid Supply)
- Cooling Liquid Return (Heated Liquid Return)
- Chilled Liquid Supply
- Chilled Liquid Return

NOTE
The use of starter CT's and PT is dependent upon the operating voltage of the starter and the input rating of the power analyzer device. This is a measurement method to be determined based on the limitations of the devices involved.
What measurements might need to be taken?

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

- **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

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

The most challenging characterizations to determine.
Combining measurements to develop a conclusion.

COP derived from (for example)

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

\[
= \frac{m \cdot c_p \cdot \Delta T + m \cdot \Delta P / \rho}{\sum W}
\]

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

\[
= \frac{V \cdot \rho \cdot c_p \cdot \Delta T + V \cdot \Delta P}{\sum W}
\]

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.

Supplemental Files

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

Files:
- An empty workbook / template
- An example calculation
- Instruments - Uncertainty examples
Workbook - Overview

Introduction to field testing of liquid chillers and ASHRAE Standard 184

Workbook Overview & Guide.
This workbook is provided in support of ASHRAE Standard 184. It supports performance verification of the systems types outlined in the standard (electric water cooled only for this revision). Calculation of chiller the performance and associated uncertainty involves many steps. The intent of this workbook is to attempt to make this as approachable as possible. Although the workbook contains many worksheets (tabs) it is segregated into colored tabs to identify the function of each tab.

Tabs
- Gray: Instructions & information, read only, no input required.
- Red: Primary configuration. Entry of the key configuration details of the system, including fluids and the units of measurement to be used.
- Blue: Input for each measurement point. One tab will need to be completed for each measurement position taken (e.g., evaporator water leaving temperature). Each tab allows for up to six independent calculations. This feature allows any calibration information to be included in the final calculations.
- Light blue: Intermediary calculations. This is for information and review only.
- Yellow: Results summary.
- Green: Support information, read only, no input required. Fluid properties, unit conversions and workbook configuration information.
- Purple: Support information, read only, no input required. Fluid properties, unit conversions and workbook configuration information.

Cells
Note: To assist with understanding where data entry is required only cells color coded with a cyan background need to be completed. All other cells are protected and do not allow data entry.

Measurement tabs
The configuration of each measurement tab is likely to be the most difficult task when using this workbook. Each tab consists of three main areas (remember, only the blue cells need input):

- Pretest estimates for uncertainty information (shaded light yellow).

Test measurement values (shaded light green)

- Revisions
- Instructions
- Checklist
- Glossary
- Input Configuration
- Calibration Template
- EvapFlow
- EvapTempIn
- EvapTempOut
- EvapPd
- CondFlow
- CondTempIn
- CondOut
**Workbook – Input Configuration Tab**

**Set the system & testing Parameters**

This tab first!

**Units of Measurement**

<table>
<thead>
<tr>
<th>Input</th>
<th>Type of Flow Measurements</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°F</td>
<td>Cooling efficiency kW/tonR</td>
</tr>
<tr>
<td>Length</td>
<td>ft</td>
<td>Heating efficiency COP</td>
</tr>
<tr>
<td>Pressure</td>
<td>psig</td>
<td></td>
</tr>
<tr>
<td>Pressure Differential</td>
<td>ftH2O(at 60°F)</td>
<td></td>
</tr>
<tr>
<td>Volume Flow Rate</td>
<td>gal/min</td>
<td></td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td>lbm/s</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>kW</td>
<td></td>
</tr>
<tr>
<td>Cooling capacity</td>
<td>tonR</td>
<td></td>
</tr>
<tr>
<td>Heating capacity</td>
<td>tonR</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>lbm/ft³</td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>Btu/(lbm·Δ°F)</td>
<td></td>
</tr>
</tbody>
</table>

**Fluid Properties**

<table>
<thead>
<tr>
<th>Evaporator (cold) Fluid</th>
<th>AHRI water properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser (hot) Fluid</td>
<td>AHRI water properties</td>
</tr>
</tbody>
</table>

(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 😊

- Set the system & testing Parameters
- This tab first!
- 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

Random uncertainties captured here

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

<table>
<thead>
<tr>
<th>Absolute</th>
<th>Estimate ISO Type</th>
<th>symbol</th>
<th>units</th>
<th>Pre-Test Estimates</th>
<th>Test Measurement Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td></td>
<td></td>
<td>100</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>ν₂</td>
<td></td>
<td></td>
<td>99</td>
<td>332</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>gal/min</td>
<td></td>
<td>10800.0</td>
<td>10835.9</td>
</tr>
<tr>
<td></td>
<td>σₓ</td>
<td>gal/min</td>
<td></td>
<td>108.0</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>Type A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.80</td>
<td>3.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative</th>
<th>Estimate ISO Type</th>
<th>symbol</th>
<th>units</th>
<th>Pre-Test Estimates</th>
<th>Test Measurement Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.56%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.03%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systematic Standard Uncertainty</th>
<th>Pre-Test Estimates</th>
<th>Test Measurement Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Distribution Type</td>
<td>Estimate ISO Type</td>
</tr>
<tr>
<td>Expansion residual error (bias error), if available use the expanded standard error</td>
<td>Normal</td>
<td>Type A</td>
</tr>
<tr>
<td>Environmental influence (ambient temperature &amp; pressure &amp; humidity, analog signal)</td>
<td>Uniform</td>
<td>Type A</td>
</tr>
<tr>
<td>Spatial location or installation effect of measurement device (add specific examples for resolution)</td>
<td>Triangular</td>
<td>Type B</td>
</tr>
<tr>
<td>Stability versus time (drift), depends on length of time since last calibration</td>
<td>Uniform</td>
<td>Type A</td>
</tr>
<tr>
<td>Other [enter another source of systematic uncertainty]</td>
<td>Triangular</td>
<td>Type B</td>
</tr>
</tbody>
</table>

Pre-test – up to 6 points

This measurement worksheet allows test setups ranging from a single redundant measurement instrument that are averaged into Only blue cells require input 😊
Workbook – Measurement Tabs

Paste test data, up to 6 instruments

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

Estimate of A to D resolution

Visualization of test data
# Workbook – Interim Results Tabs

## Introduction to Field Testing of Liquid Chillers and ASHRAE Standard 184

### Pre-test and Test Visualization

Results for Pre-test and Test

### Interim Results Tabs

<table>
<thead>
<tr>
<th>Description</th>
<th>Pre-Test</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap liquid volume flow rate</td>
<td>V-ev</td>
<td>V-ev</td>
</tr>
<tr>
<td>unused</td>
<td>unused</td>
<td></td>
</tr>
<tr>
<td>Evap liquid density at flow meter</td>
<td>p-ev-in</td>
<td>p-ev-in</td>
</tr>
<tr>
<td>unused</td>
<td>unused</td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom, Systematic Uncertainty</td>
<td>η_1</td>
<td>50</td>
</tr>
<tr>
<td>Degrees of Freedom, Random Uncertainty</td>
<td>η_2</td>
<td>99</td>
</tr>
<tr>
<td>Effective Degrees of Freedom</td>
<td>η_1</td>
<td>99</td>
</tr>
<tr>
<td>Absolute Systematic Standard Uncertainty</td>
<td>η_1</td>
<td>10880</td>
</tr>
<tr>
<td>Absolute Random Standard Uncertainty</td>
<td>s_1</td>
<td>62.4147867</td>
</tr>
<tr>
<td>Absolute Combined Standard Uncertainty</td>
<td>s_1</td>
<td>62.4156516</td>
</tr>
<tr>
<td>Sensitivity Coefficient</td>
<td>η</td>
<td>8.3436436</td>
</tr>
<tr>
<td>Contribution to the Combined Uncertainty of Random Standard Uncertainty</td>
<td>η_1</td>
<td>1443.75</td>
</tr>
<tr>
<td>Contribution to the Combined Uncertainty</td>
<td>η_1</td>
<td>3122876.43</td>
</tr>
<tr>
<td>Contribution to the Combined Uncertainty of the Result</td>
<td>η_1</td>
<td>20300.137</td>
</tr>
<tr>
<td>Contribution to the Combined Uncertainty of the Result</td>
<td>η_1</td>
<td>775.619357</td>
</tr>
<tr>
<td>Contribution to the Standard Uncertainty of the Result</td>
<td>η_1</td>
<td>93.67%</td>
</tr>
<tr>
<td>Contribution to the Standard Uncertainty of the Result</td>
<td>η_1</td>
<td>0.24%</td>
</tr>
<tr>
<td>Contribution to the Standard Uncertainty of the Result</td>
<td>η_1</td>
<td>6.09%</td>
</tr>
<tr>
<td>Contribution to the Standard Uncertainty of the Result</td>
<td>η_1</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

### Units for Conversion

<table>
<thead>
<tr>
<th>Unit Numerator</th>
<th>Unit Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>gal</td>
<td>lbm</td>
</tr>
<tr>
<td>min</td>
<td>ft²</td>
</tr>
</tbody>
</table>

### Unit Conversion Calculation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.13368056</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Interim Results Tabs

- Pre-test
- Test

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Introduction to field testing of liquid chillers and ASHRAE Standard 184
Introduction to field testing of liquid chillers and ASHRAE Standard 184

### Summary for Pre-test and Test

#### Evaporator

<table>
<thead>
<tr>
<th>Units of Measure</th>
<th>Average Value</th>
<th>Uncertainty Value</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering Fluid Temp.</td>
<td>52.77°F</td>
<td>±0.24°F</td>
<td>±0.023°F</td>
</tr>
<tr>
<td>Leaving Fluid Temp.</td>
<td>42.01°F</td>
<td>±0.24°F</td>
<td>±0.023°F</td>
</tr>
<tr>
<td>Fluid Temp. Diff.</td>
<td>10.76°F</td>
<td>±0.33°F</td>
<td>±3.1%</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>1084 gal/min</td>
<td>±70 gal/min</td>
<td>±6.2%</td>
</tr>
<tr>
<td>Net Capacity</td>
<td>292.50 tonR</td>
<td>±12.00 tonR</td>
<td>±4.1%</td>
</tr>
</tbody>
</table>

#### Condenser

<table>
<thead>
<tr>
<th>Units of Measure</th>
<th>Average Value</th>
<th>Uncertainty Value</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering Fluid Temp.</td>
<td>85.65°F</td>
<td>±0.24°F</td>
<td>±0.021%</td>
</tr>
<tr>
<td>Leaving Fluid Temp.</td>
<td>94.55°F</td>
<td>±0.24°F</td>
<td>±0.021%</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>8.51°F</td>
<td>±10.33°F</td>
<td>±13.7%</td>
</tr>
<tr>
<td>Net Capacity</td>
<td>334.80 tonR</td>
<td>±16.00 tonR</td>
<td>±4.7%</td>
</tr>
</tbody>
</table>

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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