Radiant Cooling Design: Performance Prediction and Modeling Methods

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Agenda

Background

Cooling load prediction methods and tools

- What’s available and what’s been used?
- Are they accurate?
- Investigation by experiment and simulation

Design recommendations

- Cooling load prediction method
- Modeling tool selection
- Implications for sizing

Modeling for code compliance and LEED
Backgrounds: Air systems vs. Radiant systems

**Air systems**
- Ventilation + space conditioning
- Design to meet a single peak cooling load value
- Remove heat using convection

**Radiant systems**
- Decoupled ventilation and space conditioning
- Allow pre-conditioning the radiant layer
- Remove heat using convection + radiation
1. Is the cooling load the same for radiant systems as for air systems?

2. Can we use the same method to size radiant system as air system?

3. Which modeling tools can be used to assist design?
What methods and tools are available and being used?

**Literature review**
- ASHRAE HOF (2013)
- ISO 11855 (2012)
- RHVEA Guidebook
- Price Engineer's HVAC Handbook (2011)

**Case studies + Survey**
- 5 case studies
- 11 responses from designers from Europe and North America

1) ASHRAE HOF; 2) ISO 11855 (2012)

<table>
<thead>
<tr>
<th>Building names</th>
<th>applications</th>
<th>Load features</th>
<th>Rad system type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankok Airport</td>
<td>Lobby/atrium</td>
<td>solar + stratification</td>
<td>radiant floor</td>
</tr>
<tr>
<td>David Brower Center</td>
<td>office</td>
<td>Typical</td>
<td>radiant ceiling slab</td>
</tr>
<tr>
<td>Walmart at sacramento</td>
<td>retail with skylight</td>
<td>Typical</td>
<td>radiant floor cooling</td>
</tr>
<tr>
<td>Manitoba Hydro</td>
<td>office</td>
<td>Typical</td>
<td>TABS ceiling</td>
</tr>
<tr>
<td>NREL Research Support Facility</td>
<td>office</td>
<td>Typical</td>
<td>radiant slab ceiling</td>
</tr>
<tr>
<td>William Jefferson Clinton</td>
<td>office</td>
<td>Typical</td>
<td>radiant floor</td>
</tr>
<tr>
<td>Presidential Library</td>
<td>Lobby/atrium</td>
<td>load+stratification</td>
<td>radiant floor</td>
</tr>
<tr>
<td>Lobby of Hearst headquarters</td>
<td>Lobby/atrium</td>
<td>solar + stratification</td>
<td>radiant floor</td>
</tr>
<tr>
<td>SMUD building office area</td>
<td>office</td>
<td>Typical</td>
<td>radiant ceiling slab</td>
</tr>
<tr>
<td>St Meinrad Archabbey church</td>
<td>Church</td>
<td>load+stratification</td>
<td>radiant floor</td>
</tr>
</tbody>
</table>

**Case study building list**
<table>
<thead>
<tr>
<th>Method</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Heat gain</td>
<td>Ignore thermal mass effect</td>
</tr>
<tr>
<td>#2 Simplified methods</td>
<td>RTS, CLTD/CLF/SCL, weighting factor method, etc. (air system only)</td>
</tr>
<tr>
<td>#3 HB method</td>
<td>Radiant system simulated with dynamic simulation tool</td>
</tr>
<tr>
<td>#4 Non-traditional</td>
<td>Used mostly for applications with intensive solar and stratification</td>
</tr>
<tr>
<td>#5 ISO-11855 (2012)</td>
<td>Diagram based on design day energy gain, operation hour, and etc. (TABS only)</td>
</tr>
</tbody>
</table>
Thermal load analysis method/tool in practice

- 13 out of 16 designers we interviewed assume the same cooling load for radiant systems as air systems
- Radiant cooled surfaces were not directly modeled

Typical design

- ISO 11855 method: 0%
- Dynamic simulation tool: 19%
- Simplified method (Trane Trace): 38%
- Directly use heat gain: 37%
- Non-traditional method (CFD, etc): 6%

N=16
Differences between Heat gain and cooling load

Thermal mass effect for convection based (air) system
(source: ASHRAE Fundamental 2013)
Space cooling load definition

What is the difference in cooling load for radiant vs. air systems?

All-air systems

- Cooling load
  - Heat gain removed by convection only
  - Maintain fixed setpoint temperature
- Radiant heat gain
  - Absorbed by non-active thermal mass
  - Released as convective heat gain after time delay

Radiant systems

- Cooling load
  - Heat gain removed by radiation and convection at active chilled surface
  - Maintain operative temperature within comfort zone
- Radiant heat gain
  - Becomes cooling load instantly
Are they the same?

\[
\text{Cooling load}_{\text{RADIANT}} \neq \text{Cooling load}_{\text{AIR}}
\]

Laboratory testing and simulation study will compare the following:

- Instantaneous cooling rate
- Peak cooling rate
Laboratory testing: Cooling load comparison

Objectives

- Verify that cooling loads for radiant system are different from air system

Experimental approach

- Concrete blocks (thermal mass) on floor with heating mats on top (internal heat gain)
- Conduct 12-hour tests with heaters on for 6 hours and off for 6 hours
  - Radiant chilled ceiling panels
  - Overhead air system
  - Maintain the same operative temperature
Test chamber configurations

Experimental results: Operative temperature

Maintain the same thermal comfort level

- Control to the same operative temperature at 24°C (75.2 °F)
Experimental results: Instantaneous cooling rate

Radiant system has a higher cooling rate than the air system

- 18% higher during hour 6 (peak cooling load)
Experimental results: Total energy removal

Radiant system removes heat faster during heater-on period

- Radiant system removes 82% of total heat gain
- Air system removes 63.3% of total heat gain
Simulation study of different design cases

Radiant system types
- Radiant panel/Lightweight radiant slab/Heavyweight radiant slab

Parameters studied
- Thermal insulation
- Building mass
- Radiative/convective split of internal load
- Solar heat gain
- Active ceiling/floor

Cooling design day simulation

Results: Peak cooling load

Higher peak cooling load for studied cases:

- Interior space: 7-27%
- Perimeter space without solar: 12-35%
- Perimeter space with solar: 48-85%

Implications

- Minimize solar load for design
- Especially effective for removing solar load
- High peak load ≠ high energy consumption!
Why are they different?

Air System

Cooling load from convective heat gain

Convective Heat Gain

Cooling load from radiative heat gain

Radiant System

Cooling load from convective heat gain

Radiative Heat Gain

Cooling load from radiative heat gain
Comparison of cooling load profiles

- Case example: Internal load only, radiative fraction = 0.6

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What about cooling load prediction methods and modeling tools?
ASHRAE cooling load prediction methods

**Heat balance (HB) method**
- Based on first principles
- EnergyPlus 8.0

**Radiant time series (RTS) method/weighting factor method**
- Convective heat gain $\rightarrow$ instantaneous cooling load
- Radiative heat gain $\rightarrow$ convective cooling load with delay
- CTF/RTF Generator and excel (or TRACE )
When radiant cooling and heating systems are evaluated, the radiant source should be identified as a room surface. The calculation procedure considers the radiant source in the heat balance analysis. Therefore, the heat balance method is preferred over the weighting-factor method for evaluating radiant systems. Strand and Pedersen (1997) describe implementation of heat source conduction transfer functions that may be used for modeling radiant panels within a heat balance-based building simulation program.

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ASHRAE Handbook of Fundamentals, (2013)
Chapter 19: Energy estimating and modeling method
Measured vs. Prediction based on HB method

- EnergyPlus v8.0 model was developed to apply the HB method
- Match well with air system cooling load
- Radiant system cooling load: heat removed by the radiant ceiling panels
• RTS method cannot predict cooling load correctly for the test chamber configuration
## Modeling tool selection

<table>
<thead>
<tr>
<th>Tools</th>
<th>Modeling method</th>
<th>Capability to capture the radiant dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>IES (VE)</td>
<td>HB method</td>
<td>😊</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>HB method</td>
<td>😊</td>
</tr>
<tr>
<td>EnergyPlus</td>
<td>HB method</td>
<td>😊</td>
</tr>
<tr>
<td>ESP-r</td>
<td>HB method</td>
<td>😊</td>
</tr>
<tr>
<td>DOE-2</td>
<td>Weighting factor method</td>
<td>😞</td>
</tr>
<tr>
<td>eQUEST</td>
<td>Weighting factor method</td>
<td>😞</td>
</tr>
<tr>
<td>TRACE</td>
<td>RTS method or TF method</td>
<td>😞</td>
</tr>
</tbody>
</table>

Make sure to:  
1) Model the radiant source as a room surface;  
2) Define cooling load correctly
Design radiant floor cooling systems with solar load

Applications

- Spaces with large glazed surfaces, such as atria, perimeter areas, etc.

Guidance is limited with solar

- Maximum cooling capacity in standard: 42 W/m² (13 Btu/h·ft²)
- With solar: 100 W/m² (32 Btu/h·ft²)

_Akron art museum, OH_

A special case for floor cooling is when there is direct sun radiation on the floor. Then the cooling capacity of the floor may exceed 100 W/m² (32 Btu/h·ft²). This is also why floor cooling is increasingly used in spaces with large glass surfaces such as airports, atriums, and entrance halls.

Simulated capacity vs. standard **without solar**

- Simulated capacity matches well with standard capacity curve without solar
Simulated capacity vs. standard with solar

- Cooling capacity can reach 130 W/m² (42 Btu/h.ft²)

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**Standard capacity curve**

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Impact on air system sizing

Air system size:  **Simulated:** 20 W/m² (6.4 Btu/h.ft²)

**Guideline:** 86 W/m² (27.5 Btu/h.ft²)

peak cooling load: 128 W/m² (41 Btu/h.ft²)

Radiant cooling capacity: 108 W/m² (34.5 Btu/h.ft²)

Cooling capacity high limit without solar 42 W/m²
Modeling for code compliance and beyond code program
Title 24 (2013): Radiant floor cooling system

- Modeling requirements for compliance evaluation

<table>
<thead>
<tr>
<th>Items</th>
<th>Modeling Input Restrictions</th>
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<tbody>
<tr>
<td>Temperature control</td>
<td>Mean air temperature</td>
</tr>
<tr>
<td>Hydronic Tubing Inside Diameter</td>
<td>Between a minimum of 1/2” and a maximum of ¾ ”</td>
</tr>
<tr>
<td>Temperature Control</td>
<td>Fixed at Mean Air Temperature for compliance calculations</td>
</tr>
<tr>
<td>Condensation Control Dewpoint Offset</td>
<td>Minimum cold water supply Temperature fixed at 2°F above dewpoint</td>
</tr>
<tr>
<td>Cooling Low Water Temperature</td>
<td>55°F</td>
</tr>
</tbody>
</table>

- EnergyPlus will be available for code compliance (CBECC-Com), Jan 2014, [http://www.bees.archenergy.com](http://www.bees.archenergy.com)
<table>
<thead>
<tr>
<th>LEED topics</th>
<th>Possible points</th>
</tr>
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<tbody>
<tr>
<td><strong>Energy &amp; Atmosphere</strong></td>
<td></td>
</tr>
<tr>
<td>Credit 1: Optimize energy performance</td>
<td></td>
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<tr>
<td>Credit 3: Enhanced commissioning</td>
<td>26</td>
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<tr>
<td>Credit 4: Enhanced refrigerant management</td>
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<tr>
<td>Credit 5: Measurement &amp; verification</td>
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<tr>
<td><strong>Indoor Environmental Quality</strong></td>
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<tr>
<td>Credit 1: Outdoor air delivering monitoring</td>
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<tr>
<td>Credit 2: Increased ventilation</td>
<td>6</td>
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<tr>
<td>Credit 3: Construction IAQ plan</td>
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<tr>
<td>Credit 6.2: Controllability of systems – thermal comfort</td>
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<tr>
<td>Credit 7: Thermal comfort- Design&amp;Verification</td>
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<tr>
<td><strong>Innovation in design</strong></td>
<td>5</td>
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Key takeaway

- **Cooling load prediction and modeling method for radiant systems**
  - Use design tools based on heat balance approach
  - Define cooling load as heat removed by actively cooled surface(s), i.e., radiant source should be modeled
  - RTS or weighting factor method, may lead to incorrect results

- **Peak cooling loads may be higher than air systems, but...**
  - Radiant systems are known to be more energy efficient
  - Under some operating strategies radiant systems will have lower peak cooling loads (e.g., nighttime pre-cooling).
Acknowledgments

• California Energy Commission (CEC) Public Interest Energy Research (PIER) Buildings Program.

• Center for the Built Environment, University of California, Berkeley (www.cbe.berkeley.edu).

• Julian Rimmer, Brad Tully, and Tom Epp of Price Industries for the use of their Hydronic Test Chamber in Winnipeg.
Radiant system building project

Link to the form: http://bit.ly/RadiantFormCBE
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Questions?

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