Energy Saving Potential of Passive Chilled Beam System as a Retrofit Option in Commercial Buildings with Different Climates

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Main Objective

Conventional Cooling System VS Passive Chilled Beam System

Energy Savings in Different Climatic Zones
Introduction of Passive Chilled Beam System

- Fin-and-Tube Heat Exchanger
- Natural Convection Driven Flow
- Passive System
- Radiation Between Indoor Surfaces
Introduction of Passive Chilled Beam System

- **Benefits**
  - End-use energy cost can be saved mostly by decoupling of sensible and latent load which results in reduced fan and chiller energy.
  - Thermal comfort can be improved by both radiation cooling effect and natural convection driven air movement.
  - Maintenance cost can be saved since chilled beam system does not include moving parts such as fans, motors, damper actuators etc.
  - Usable space can be saved by using smaller water pipes instead of larger air ducts.
  - Sound level in the space can also be reduced.

- **Drawbacks**
  - High installation cost
  - Condensation risk
  - Risk of water leak

FOCUS ON,
Energy savings potentials by decoupling sensible and latent load
Building Energy Model Description

- Climatic Data

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Selected Cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Miami</td>
</tr>
<tr>
<td>2A</td>
<td>Houston</td>
</tr>
<tr>
<td>3A</td>
<td>Atlanta</td>
</tr>
<tr>
<td>4A</td>
<td>Philadelphia</td>
</tr>
<tr>
<td>5A</td>
<td>Lafayette</td>
</tr>
<tr>
<td>2B</td>
<td>Phoenix</td>
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<td>3B</td>
<td>L.A.</td>
</tr>
<tr>
<td>4B</td>
<td>Prescott</td>
</tr>
<tr>
<td>5B</td>
<td>Salt Lake City</td>
</tr>
<tr>
<td>3C</td>
<td>San Francisco</td>
</tr>
<tr>
<td>4C</td>
<td>Seattle</td>
</tr>
</tbody>
</table>
Building Energy Model Description

- Building Envelope Parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Layer Description</th>
<th>Thickness m</th>
<th>U-Value W/m²K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>Insulation</td>
<td>0.1</td>
<td>0.221</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>0.038</td>
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</tr>
<tr>
<td>Raised Floor</td>
<td>Concrete</td>
<td>0.3</td>
<td>0.086</td>
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<tr>
<td></td>
<td>Air</td>
<td>0.102</td>
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<tr>
<td>External Wall</td>
<td>Gypsum Board</td>
<td>0.013</td>
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<tr>
<td></td>
<td>Insulation</td>
<td>0.105</td>
<td>0.358</td>
</tr>
<tr>
<td></td>
<td>Stucco</td>
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</tr>
<tr>
<td>Internal Wall</td>
<td>Gypsum Board</td>
<td>0.016</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>0.184</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Board</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>Double pane, Low-e, IGU</td>
<td>-</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Living Lab 1 has 117 m² floor area with the height of 4.6 m. North, east and bottom side of the space is adjacent with other spaces in the building and south and west walls are exposed to the ambient. The window to wall ratio is about 50% on the South wall.
Building Energy Model Description

Internal Gains

- **Occupant load factor**
  - Peak Occupancy: 10 people
  - Type: seated, working
  - Sensible heat [W]: 75
  - Latent heat [W]: 75

- **Plug load factor**
  - Number of PCs: 10
  - Heat gain [W/PC]: 140 W/PC

- **Lighting load factor**
  - Lighting Power Density [W/m²]: 10 W/m²
  - Convective Portion [%]: 40

Internal gain schedules for occupancy, lighting and plug loads were adopted from ASHRAE Standard 90.1. These schedules represent typical load profiles of commercial building.
Building Energy Model Description

- Control Sequence of Conventional All-Air System

“Air system’s operation sequence follows sensible load”

<table>
<thead>
<tr>
<th>Component</th>
<th>Control Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Fan Speed (Fan 1)</td>
<td>Modulate to meet room temp. setpoint (23.9°C)</td>
</tr>
<tr>
<td>Pump Speed (Pump 1)</td>
<td>Modulate to meet cooling coil outlet air temp. setpoint (13°C)</td>
</tr>
<tr>
<td>Return Fan Speed (Fan 2)</td>
<td>Synchronized with the supply fan</td>
</tr>
<tr>
<td>Chiller</td>
<td>Modulate to provide 7°C outlet temp. whenever the cooling signal is on</td>
</tr>
<tr>
<td>Economizer</td>
<td>Control based on temp. difference between room setpoint and outdoor air</td>
</tr>
</tbody>
</table>
Building Energy Model Description

Control Sequence of Passive Chilled Beam (PCB) System

“Air system’s operation sequence follows latent load, chilled beam follows remaining sensible”

<table>
<thead>
<tr>
<th>Component</th>
<th>Control Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump 1, Fan 2, Chiller, Econ.</td>
<td>Same as conventional system’s sequence</td>
</tr>
<tr>
<td>Supply Fan Speed (Fan 1)</td>
<td>Modulate to meet room humidity setpoint (0.01 kg_{water}/kg_{air})</td>
</tr>
<tr>
<td>Pump Speed (Pump 2)</td>
<td>Modulate to meet outlet temp. setpoint (9°C) when chilled beam operation is required</td>
</tr>
<tr>
<td>Pump Speed (Pump 3)</td>
<td>Constant speed ON/OFF control when chilled beam operation is required</td>
</tr>
<tr>
<td>Passive Chilled Beam</td>
<td>Modulates the number of units from 1 to MAX to meet the room temp. setpoint (23.9°C)</td>
</tr>
</tbody>
</table>
Building Energy Model Description

- **HVAC Components**

  ![Fan Model](image1)
  ![Pump Model](image2)
  ![Passive Chilled Beam Model](image3)

  - **Affinity Laws**
  - **2nd order polynomial**
  - **Convective Model**

- **Additional Control Setups**

<table>
<thead>
<tr>
<th>Control Logic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night Setback</td>
<td>Room temp. setpoint or room humidity setpoint is increased (+4°C, +0.003 kg_{water/kg_{air}}) besides occupied hours (0800-1700hrs)</td>
</tr>
<tr>
<td>Minimum Ventilation</td>
<td>Minimum outdoor air requirement based on ASHRAE Standard 62.1 was applied. At least 0.4 ACH outdoor air is included in supply air stream.</td>
</tr>
</tbody>
</table>
Modeling Results

- Energy Saving Benefits of Using Passive Chilled Beam System

- Reduced fan energy

While fan’s power is driven only by the sensible load in conventional scenario, it is driven only by the latent load in PCB scenario. Thus, since the magnitude of latent load is always smaller than sensible load in every climates, fan energy is always saved in PCB scenario.
Modeling Results

- Energy Saving Benefits of Using Passive Chilled Beam System
  - Reduced chiller energy in favorable climate

In climates where the relative portion of latent load compare to sensible load is small, an excess dehumidification might have been provided, since the air system is driven by the profile of sensible load in conventional scenario.

Thus, there is an opportunity to save energy on chiller side with the amount difference between excess dehumidification and actual latent load (which is the difference between dotted and solid blue curve shown in above graph).
Modeling Results

- Energy Consumption for Cooling Season Between Scenarios

**Conventional System**

**Passive Chilled Beam System**

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1A</th>
<th>2A</th>
<th>3A</th>
<th>4A</th>
<th>5A</th>
<th>2B</th>
<th>3B</th>
<th>4B</th>
<th>5B</th>
<th>3C</th>
<th>4C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cities</td>
<td>Miami</td>
<td>Houston</td>
<td>Atlanta</td>
<td>Philadelphia</td>
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Fan energy can be saved more than 70% in every region,
Chiller energy can be saved 8-17% besides in marine region (3C, 4C).
Modeling Results

- Relative Energy Savings in Each Climatic Zone

13-17% savings in humid region (A), 8-24% savings in dry region (B) linearly depending on the magnitude of sensible load, negative or almost no savings in marine region (C).

### Selected Cities in Each Climate Zone

<table>
<thead>
<tr>
<th>Climate</th>
<th>1A</th>
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<th>2B</th>
<th>3B</th>
<th>4B</th>
<th>5B</th>
<th>3C</th>
<th>4C</th>
</tr>
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</table>
Modeling Results

- Energy Delivered by Cooling System in Each Scenario

Above graphs are showing the total load reduction in regions besides marine region (C). While both scenarios provide about the same sensible load (blue+yellow bars) to the space, dehumidification (red bars) is mostly about 50% in PCB scenarios compared to conventional scenarios.

<table>
<thead>
<tr>
<th>Selected Cities in Each Climate Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Miami</td>
</tr>
</tbody>
</table>
Conclusions

- The following conclusions were found in considering a passive chilled beam system as a retrofit option:
  
  - Total energy savings can be achieved between **8 to 24%** in humid and dry climate zones.

  - Passive chilled beams as a retrofit option was **not favorable in marine regions**.

  - **Substantial fan energy can be saved** in every climate (~70%) depending on the magnitude of the latent load.

  - **Chiller energy can be saved** in both humid and dry regions.
Q&A
Appendix
The study considers a standard retrofit of a commercial building with minimum modification by using a passive chilled beam system in different climates. Typical single duct VAV system is widely accepted in large office buildings was considered as a baseline scenario, and a combination of the available air system and passive chilled beam system was considered as a scenario.

There are various benefits of using passive chilled beam system besides reduced energy consumption such as less noise, less ductwork and improved thermal comfort. However, since the cost of passive chilled beam system is the major barrier of introducing the system into the place, this study focuses on passive chilled beam system as a standard retrofit option with minimum modification of the original cooling system. In other words, the study is focusing on the magnitude of energy savings rather than the physical benefits.

The standard retrofit with minimum modification in this study includes installations of (1) multiple chilled beam units, (2) additional pump(s) and a closed water loop for the passive chilled units and (3) a heat exchanger where the chilled beam’s water loop exchanges heat with the side of the chilled water loop.

Following conclusions were found in considering a passive chilled beam system as a retrofit option:

- Energy savings between 8 to 24% in humid and dry climate zones.
- Use chilled beams as a retrofit option was not favorable in marine regions.
- Fan energy can be saved (~70%) depending on magnitude of latent load.
- Energy can be saved in both humid and dry regions.
Climate Zones

Marine (C) - Locations meeting all four criteria:
- Mean temperature of coldest month between –3°C and 18°C.
- Warmest month mean < 22°C.
- At least four months with mean temperatures over 10°C.
- Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Dry (B) - Locations meeting the following criteria: not marine and
- \( P_{cm} < 2.0 \times (T_C + 7) \)
- Where, \( P = \) annual precipitation, cm, \( T = \) annual mean temperature, °C

Moist (A) - Locations that are not marine and not dry.
Modeling Results

Thermal Conditions of Each Scenario – mean values during occupied hrs

**Conventional System**

- Temperature [°C]
- Humidity [%]
- PMV
- Zone Temperature [°C]

**Passive Chilled Beam System**

- Temperature [°C]
- Humidity [%]
- PMV
- Zone Temperature [°C]
Modeling Results
Envelope Load Profiles
Roofing Model

Envelope Specifications

Internal Wall East

- 5/8" GWB (EACH SIDE)
- 3 5/8" METAL STUDS

Internal Wall North

- 5/8" GWB
- 3 5/8" METAL STUDS

Materials:
- ALUMINUM COMPOSITE PANEL
- 7/8" CFM HAT CHANNEL
- RIGID INSULATION - TYPE 1
- 2" CFM FURRING
- SPRAY APPLIED AIR/WATER/VAPOR BARRIER
- 1/2" EXT. SHEATHING
- 6" CFM STUD
- 5/8" GWB

Dimensions:
- 4 7/8"
Envelope Load Characteristics based on Lafayette Climate

- Peak loads

<table>
<thead>
<tr>
<th>Load Type</th>
<th>kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak$_{sen}$</td>
<td>6</td>
</tr>
<tr>
<td>Peak$_{lat}$</td>
<td>2</td>
</tr>
<tr>
<td>Peak$_{tot}$</td>
<td>8</td>
</tr>
</tbody>
</table>

- Sensible and latent load profile

![Graph showing sensible and latent load profile](image-url)