A Case Study of Energy and Condensation Analysis for Chilled Beam Systems in the Office Building Located in Hot and Humid Climate Zone

Kuei-Peng Lee ¹, Kuan-Ting Lin ¹ and Bo-Huei Wu ¹

¹ Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, 1, Sec. 3, Chung-hsiao E. Rd., Taipei, Taiwan, 10608, ROC

ABSTRACT
This study conducted energy simulation analysis on chilled beam system in the office building located in hot and humid climate zone. It compared energy performance of three systems, including variable air volume system, fan coil unit system, and chilled beam system, which are all served by ice thermal storage systems. Besides the energy analysis, it discussed the coil condensation situations of chilled beam systems through the year and the impact of accidental infiltration rate on condensation.

This study on energy and condensation analysis was conducted by EnergyPlus simulation program. The energy saving percentage of the chilled beam system was 12.7% compared with the variable air volume system and 10.4% compared with the fan coil unit system, respectively. The electricity bill saving percentage of the chilled beam system was 19.2% compared with the chilled beam system without ice storage system. The results indicated that when the accidental infiltration as high as 0.6 ACH will cause condensation on coil.

INTRODUCTION
Illumination, electrical equipment and air-conditioning systems are the main energy-consuming items of commercial buildings, and the air-conditioning systems have the largest proportion. According to the literatures in hot and humid climate zone, the power consumption of air-conditioning systems accounts for 50% of office buildings (Bureau of Energy 2013). Therefore, innovative energy-saving air-conditioning systems are discussed and designed continuously, such as the chilled beam system. The chilled beam system has become practiced in the cool and dry climate zones of the world. The U.S. began to use it in practice and study the energy efficiency several years ago. However, in hot and humid climate zone, e.g. Taiwan, there are few design cases, the owners and designers still sit on the fence considering the economic cost and the risk of condensation.

Regarding the energy-saving and economic cost subjects of chilled beam, Jeff Stein et al. 2013 studied VAV with reheat system and active chilled beam with dedicated outdoor air system (DOAS), and used EnergyPlus to simulate the energy consumption and construction cost. The results showed that the energy consumption of VAV with reheat system was 40% lower than the active chilled beam with DOAS, the cooling energy consumption was reduced by 28%, the heating energy consumption was reduced by 70%, the fan energy consumption was reduced by 60%. The initial cost of active chilled beam with DOAS is 1.4 times of VAV with reheat system, its cost payback years is 80 years. Peter Rumsey et al. 2005 used DOE-2 to compare the energy consumption and economy of comprehensive energy-saving technique of chilled beam, heat recovery, natural cooling, waste-heat power generation and solar power generation with that of standard system design for the research center in Nevada. Compared with the standard system design, the system reduced the energy consumption by 57%, and the initial cost was reduced by about 2.6%. Li 2011 discussed the air distribution performance and energy-saving benefit of chilled beam air supply system, and proposed countermeasures against the risk of condensation and precooling operation for the countries and regions in tropical and subtropical climate zones (e.g. Taiwan), and compared the power consumption and payback period of investment of variable air volume system with that of chilled beam system by evaluating an office building case in Taipei. The evaluation result of simple calculation showed that the energy consumption of chilled beam was about 727kW lower than the variable air volume system, and the payback period of investment of the chilled beam system was 2.01 years. Steve Weidner et al. 2009 designed a customer service center in Kentucky, U.S., studied the combination of underfloor air distribution (UFAD) and other passive cooling equipment, and found that combining chilled beam with UFAD reduced the air output, the power consumption was reduced by 41%, the natural gas consumption was reduced by 24%. The energy consumption was reduced obviously, and the thermal comfort was good.

In order to avoid the active chilled beam becoming an expensive air outlet as the air volume is increased, Andrey Livchak et al. 2012 discussed the design of minimum air volume chilled beam and how to enhance the performance of chilled beam. Jan Fredriksson et al. 2009 discussed the effect of the coverage of ceiling on the cooling effectiveness of passive chilled beam. The findings showed that in order to maximize the cooling effectiveness of chilled beam with homogeneous source, there should be adequate space for heat exchange, and the air circulation in the entire space must be considered, so that the cooling effect could be optimized.

To sum up the existing literatures, the energy-saving effect of chilled beam seems to depend on the design case, and the air infiltration in hot and humid climate zone which may result in condensation of chilled beam is not probed into. Therefore, this study simulates and analyzes the energy consumption of common fan coil unit, VAV system and chilled beam in Taiwan in the hot and humid climate zone, and discusses the risk of condensation of chilled beam.

SIMULATION
This study uses EnergyPlus energy simulation program to model the real case, as shown in Figure 1. This building is a northeastward office building, 11 stories above ground and 4 stories under ground. The 2nd and the 3rd floor are main instructional space, the other floors have meeting rooms and office space. This study analyzes the energy saving of the office space with the chilled beam system; the key point is to comparatively analyze the energy saving and condensation of chilled beam by simulation.
The main space types of this case include instructional space, office space, conference space and corridor space. The service intensities of lighting and equipment at weekdays and weekend are shown in Figures 2–5. The space load densities are shown in Table 1. The air-conditioning system equipment of this building include two centrifugal chillers, two cooling towers, the air conditioning hot-water system uses water source heat pump, 14 water circulating pumps of chilled water loop and hot water loop. The detail specifications of water side system equipment are shown in Tables 2–7.

Chilled beams of this case are available in two variations: active chilled beam (ACB) and passive chilled beam (PCB). The chilled beam equipment specification of this case is shown in Table 8. In the EnergyPlus simulation model, the heat transfer rate per unit length of chilled beam is calculated by the following equation, expressed as Eq. (1):

\[ P_{beam} = A \times K \times \Delta T \]  

(1)

where the coil heat transfer coefficient \( K \), the air mass flow rate \( \nu_{\rho} \) through coil and the volume flow rate \( q_{in} \) through coil per unit length are expressed as Eqs. (2)–(4):

\[ K = \alpha \times \Delta T^{n_1} \times \nu_{\rho}^{n_2} \times \omega^{n_3} \]  

(2)

\[ \nu_{\rho} = \frac{q_{in}}{\alpha_0} \times \rho_{air} \]  

(3)

\[ q_{in} = K_1 \times \Delta T^{n_1} + K_{in} \times q_{pr} \]  

(4)

where

- \( A \): Effective area of coil per unit length
- \( \Delta T \): Temperature difference between air flow in space and chilled water
- \( \omega \): Chilled water flow velocity
- \( q_{pr} \): Air supply per unit length

The correlation coefficient of Eqs. (2)–(4) is shown in Table 9.

In order to make the energy consumption analysis of this paper further meet the actual situation, the fan for the active chilled beam system refers to the MAU in the equipment specification sheet; the fan of the VAV system refers to ASHRAE90.1-2007; the FCU system refers to the fan coil unit of Taiwan green building assessment manual EEWH 2015. The details are shown in Table 10.
**Table 1 Space load density**

<table>
<thead>
<tr>
<th>Type</th>
<th>Person</th>
<th>Lighting</th>
<th>Equipment</th>
<th>Outside air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>m²/person</td>
<td>W/m²</td>
<td>W/m²</td>
<td>ACH</td>
</tr>
<tr>
<td>Class</td>
<td>8</td>
<td>16</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>Office</td>
<td>8</td>
<td>13</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>Corr</td>
<td>13</td>
<td>13</td>
<td>20</td>
<td>1.8</td>
</tr>
<tr>
<td>Conf</td>
<td>3</td>
<td>15</td>
<td>30</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 2 Chiller schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Cap.</th>
<th>Power RT kW</th>
<th>Evaporator</th>
<th>Condenser</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-1,2</td>
<td>600</td>
<td>110.40</td>
<td>12</td>
<td>121.09</td>
<td>Water</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>110.40</td>
<td>-2.2</td>
<td>-5.5</td>
<td>Brine</td>
</tr>
</tbody>
</table>

**Table 3 Cooling tower schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Cap.</th>
<th>Flow rate</th>
<th>EWT</th>
<th>LWT</th>
<th>WBT</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>RT L/S</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
<td>HP</td>
<td></td>
</tr>
<tr>
<td>CT-1,2</td>
<td>600</td>
<td>121.09</td>
<td>37</td>
<td>32</td>
<td>29</td>
<td>19°</td>
</tr>
</tbody>
</table>

**Table 4 Heat pump schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Cap.</th>
<th>Power RT kW</th>
<th>Evaporator</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Screw Comp. Power</td>
<td>Flow rate</td>
<td>EWT</td>
<td>LWT</td>
</tr>
<tr>
<td>HR-1,2</td>
<td>72</td>
<td>19.58</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 5 Pump schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Cap.</th>
<th>Screw Comp. Power</th>
<th>Evaporator</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Flow rate</td>
<td>EWT</td>
<td>LWT</td>
<td>Cap</td>
</tr>
</tbody>
</table>

**Table 6 Heat exchanger schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Loop Cap.</th>
<th>Primary side</th>
<th>Secondary side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Charge cycle</td>
<td>Discharge cycle</td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td>Flow rate</td>
<td>EWT</td>
<td>LWT</td>
</tr>
</tbody>
</table>

**Table 7 Ice thermal storage schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Cap.</th>
<th>Charge cycle</th>
<th>Discharge cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>EWT</td>
<td>LWT</td>
<td>Flow rate</td>
</tr>
<tr>
<td>IC-1~7</td>
<td>RTh</td>
<td>°C</td>
<td>°C</td>
</tr>
</tbody>
</table>

**Table 8 Chilled beam schedule**

<table>
<thead>
<tr>
<th>No.</th>
<th>Qty</th>
<th>Primary air</th>
<th>Design cond.</th>
<th>Chilled water</th>
<th>Demission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Cap.</td>
<td>Power</td>
<td>Evaporator</td>
<td>Condenser</td>
<td>Flow rate</td>
</tr>
<tr>
<td>CH-1</td>
<td>675</td>
<td>22</td>
<td>12</td>
<td>13.7</td>
<td>250</td>
</tr>
<tr>
<td>CH-2</td>
<td>41</td>
<td>22</td>
<td>12</td>
<td>13.7</td>
<td>375</td>
</tr>
<tr>
<td>PC</td>
<td>181</td>
<td>22</td>
<td>12</td>
<td>15.1</td>
<td>250</td>
</tr>
</tbody>
</table>

**Table 9 Chilled beam model correlation coefficient**

<table>
<thead>
<tr>
<th>α</th>
<th>n1</th>
<th>n2</th>
<th>n3</th>
<th>α₀</th>
<th>K1</th>
<th>n</th>
<th>KKn</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.3</td>
<td>0.84</td>
<td>0.12</td>
<td>0.171</td>
<td>0.005</td>
<td>0.4</td>
<td>2.0/0.0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 10 Fan equipment efficiency**

<table>
<thead>
<tr>
<th>System</th>
<th>Active Chilled Beam</th>
<th>VAV</th>
<th>FCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan equipment efficiency (kW/(L/s))</td>
<td>0.00329</td>
<td>0.0024</td>
<td>0.000541</td>
</tr>
</tbody>
</table>

**DISCUSSION AND RESULT ANALYSIS**

**Energy Analysis**

Figure 6 shows the annual power consumption of the building in three system schemata. Table 11 shows the annual detailed power consumption of air-conditioning systems. The results show that the lighting power consumption and miscellaneous equipment power consumption are identical. The power consumption of air-conditioning equipment varies with the system characteristics and equipment efficiency. The VAV
system has the maximum energy consumption among the chillers, and then the FCU system, the chilled beam system has the minimum energy consumption. Since this case uses ice thermal storage system, the chiller energy consumption accounts for a high proportion of total energy consumption of the building.

The energy consumption of fan motor depends on the equipment efficiency and requirements for air volume and pressure. The fan of VAV system has the maximum energy consumption, and then FCU system, the chilled beam system has the minimum energy consumption. The water pump of FCU system has the maximum energy consumption, and then the chilled beam, the VAV system has minimum energy consumption. The energy consumption of heat pump for heating shows the result opposite to the fan power consumption. The lower the fan power consumption is, the less is the fan heat dissipation, higher heating capacity is required in cold season.

<table>
<thead>
<tr>
<th>System</th>
<th>Chilled beam</th>
<th>VAV</th>
<th>FCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller [kWh]</td>
<td>2,245,765</td>
<td>2,586,535</td>
<td>2,541,604</td>
</tr>
<tr>
<td>Heat Pump [kWh]</td>
<td>104,034</td>
<td>43,142</td>
<td>96,945</td>
</tr>
<tr>
<td>Fan [kWh]</td>
<td>300,430</td>
<td>557,938</td>
<td>382,725</td>
</tr>
<tr>
<td>Pump [kWh]</td>
<td>790,989</td>
<td>763,742</td>
<td>816,984</td>
</tr>
<tr>
<td>Cooling Tower [kWh]</td>
<td>172,443</td>
<td>187,488</td>
<td>194,932</td>
</tr>
<tr>
<td>Total [kWh]</td>
<td>3,613,662</td>
<td>4,138,845</td>
<td>4,033,191</td>
</tr>
</tbody>
</table>

The result of energy-saving rate of air-conditioning systems shows that the chilled beam system saves 12.7% of energy consumption compared with the VAV system; and the chilled beam system saves 10.4% of energy consumption compared with the FCU system.

Condensation Analysis

In the hot and humid climate zone, the first concern about chilled beam system is the risk of condensation. Figure 8 shows the changes in the chilled beam temperature and space dew-point temperature in 8,760 hours of a year of this building with air infiltration 0.5ACH (Air Change per Hour). The risk of condensation is very high in summer, because Taiwan is hot and humid in summer, the building airtightness is poor, the outside air infiltrates into the air conditioning space, increasing the humidity or temperature, resulting in condensation. The simulation result of this case with air infiltration 0.5ACH is shown in Figure 9, there is a certain difference between the chilled beam temperature and indoor dew-point temperature, eliminating the risk of condensation. According to this section, if the leakage is 0.6ACH, the condensation occurs. The condensation can be prevented if the leakage of building is 0.5ACH. Therefore, 0.5ACH is used in the simulation process of this paper.

Table 12 Electric charges of air-conditioning systems with and without ice storage

<table>
<thead>
<tr>
<th>System</th>
<th>With ice storage</th>
<th>Without ice storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller Beam</td>
<td>$132,661</td>
<td>$164,196</td>
</tr>
<tr>
<td>VAV</td>
<td>$159,380</td>
<td>$200,815</td>
</tr>
<tr>
<td>FCU</td>
<td>$169,348</td>
<td>$199,711</td>
</tr>
</tbody>
</table>
Taiwan has high temperature and high humidity climate in summer as it is located in the hot and humid climate zone. In this case, the condensation occurs when the outside air infiltration rate is 0.6ACH. However, the condensation can be avoided when the outside air infiltration rate is lower than 0.5ACH, the direct effect of outside air infiltration rate on the indoor air temperature and humidity is apparent. On rainy or fine summer days, instantaneous outside air infiltration increases the relative humidity of space obviously, and the temperature rise is apparent only on fine summer days.

The findings show that the chilled beam saves 12.7% of energy consumption compared with VAV system; the chilled beam saves 10.4% of energy consumption compared with FCU system. The chilled beam system with ice storage saves 19.2% of electric charge annually compared with the chilled beam system without ice storage; the VAV system saves 20.6% of electric charge annually; the FCU system saves 15.2% of electric charge annually.

CONCLUSIONS
This study uses energy simulation to study the energy efficiency of office building with chilled beam system. Besides the building energy consumption, the condensation of chilled beam is discussed, so as to perfect the chilled beam system.

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