Experimental and Numerical Analysis of a Heat Pump Driven Chilled Ceiling and Floor Heating Systems in a Test Room

Deniz Yılmaz¹, Ali Ozyurt², Ozkal Sonmez³

¹Mechanical Engineering, Arel University, Marmara University, Istanbul University Türkoba, Erguvan Sk. 26 / K, 34537 Tepekent / Büyükçekmece/İstanbul/Turkey
*¹denizy.80@gmail.com
²ali.ozyurt1293@gmail.com
³ozkalsonmez@gmail.com

Abstract

Passive cooling covers the natural processes of heat dissipation and heat gain operations and provides high efficient, comfortable environment around. As commonly known, when the air heated it rises, when cooled it descends. Natural cooling and heating use this physical property of air to provide the best thermal conditions.

In this study, an air to air heat pump system used for both floor heating and chilled ceiling operations was analyzed numerically and experimentally. Main objective of this study is to obtain COP of the heat pump system from refrigerant, hydronic and air sides. In order to calculate the air side capacity, counter loads installed into the room and the system was observed whether it provides comfort conditions. The test room was constructed of 120 mm PU panels to minimize the heat loss. All the data obtained from the system is recorded on a time period of per-second based during the processes. On the other hand, CFD analysis was performed with respect to the desired conditions on ANSYS Fluent 15. Air velocity, humidity and temperature distributions are analyzed inside the room.

Key words: Chilled Ceiling, Floor Heating, Heat Pump, CFD

1. Introduction

In our day, it is enormously important to achieve as much comfortable, sanitary as cost and energy efficient environment inside the office buildings, hospitals, education and state buildings. Passive chilled beams are gradually come into use for providing required conditions in this places.

The radiant cooling effect of the chilled ceiling surface and the convective cooling effect of air seeping down through creates a comfortable indoor environment.
Having been manufactured, these devices have to be tested in accordance with some standards in Turkey as well as Europe. One of that EN 14518:2005 has been prepared by Technical Committee CEN / TC 156. This European Standard specifies test conditions and methods for the determination of the cooling capacity of chilled beams or other similar systems with free convection i.e without forced air flow.

According to some instructions in the test standard, the test room has been designed as 5 m length and 3 m width. Surrounding walls are insulated with 120 mm PU panels to minimize the heat loss. Three chilled beam devices which are at the same properties are suspended to the ceiling with 300 mm space. The test objects were also installed symmetrically about the centre ceiling and with the longest side parallel to the longest room side. Besides, 750 W, 1000 W and 1250W resistances are representing the heat loads inside room.

The first aim when testing the chilled beams driven by heat pump, is to investigate whether the devices provide required capacity in both summer and winter conditions. To obtain capacity values, hydronic line and air side temperatures were measured respectively. Room temperature is also investigated for keeping steady state conditions and controlling the hydronic unit. To calculate the COP of heat pump unit, the refrigerant capacity that gives the exchanger for conditioning the water was also calculated. Test room set values for summer 24° C %50 RH and for winter 22° C %50 RH.

Figure 1. 2700x 600 mm PCB Panels
Figure 2. Ceiling is fully insulated
Heat Pump Specifications and Schematic Diagram

Heat Pump operation goes by this way; water is been cooled through the exchanger and then pumped to the water tank. Compressor turn on and off according to NTC sensor inside the tank. Another pump circulates the water inside the tank to the devices. This unit is controlled according to the NTC sensor inside the room. ±2° K offset stated to reactivate the pump on this unit. Heat Pump operation diagram is shown in Figure 3.

![Figure 3. Heat Pump and Hydronic Unit Schematic Diagram](image)

Determining the cooling load

Three different loads are come into account when calculating the cooling load. These loads are simulated by 3 electrical resistances (Figure 4) with same capacities and 2 of them are placed on sides of the room and one in the middle of the room.
Chilled beam devices first have to meet the cooling requirement in summer condition. When heat gain is calculated, a typical insulated wall was taken into account, shown in Figure 5. Specific heat gain passing through the walls was approximately calculated (Table 1). Environment conditions were taken 34°C for Istanbul in summer season. In addition, miscellaneous factors that contribute heat gain (e.g. lighting, sun energy, people, electronic equipments) were added and total heat gain was calculated to simulate those inside the test room. Also a humidifier was placed to provide the latent heat generated by human activation and environment. Simulated heat gain table is shown following.

### Table 1. Heat Gain table with respect to insulated wall.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Wall Elements</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/αi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plaster</td>
<td>0,02</td>
<td>0,87</td>
<td>0,023</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal coring brick</td>
<td>0,19</td>
<td>0,45</td>
<td>0,42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation material</td>
<td>0,06</td>
<td>0,04</td>
<td>1,5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plaster</td>
<td>0,005</td>
<td>0,87</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/αe</td>
<td></td>
<td></td>
<td>0,04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunlight energy through windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>Latent Heat (Humidity)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Other loads in the room</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,11</td>
</tr>
</tbody>
</table>

| AT                     | 0,47                                   | 70                      | 94               |                                        |                            |                       |

The only heat loss occurred is through the room panels to the environment. Test room panels consist of **120 mm Polyurethane foam** of the coefficient of heat transfer is **0,03 W/m.K**. Heat loss calculations were assumed that through the 6 sides of the room and depicted in Figure 6. Environment conditions are based on the temperature of the day when test operations run out.
Hence, environment temperature is **13°C** at that day. As we said before, room summer set value is **24°C %50 RH**. Heat transfer through the panels according to these informations;

\[
A; \quad \text{Heat transfer area} \quad 55 \text{ m}^2 \\
U; \quad \text{Coefficient of Insulation} \quad 0.03 \text{ W/m.K} \\
\Delta T; \quad \text{Temperature difference} \quad 24-13 = 11° K \\
Q_p ; \quad \text{Total Heat Loss (U.A.(\Delta T)/l)} \quad 165 \text{ W}
\]

**Test Methods**

The cooling capacity of the test object was determined from measurements of the cooling water flow rate and cooling water temperature rise under steady state condition. The cooling capacity was presented as a function of the temperature difference between the reference air on coil temperature and the mean cooling water temperature.

**Measurements**

The measurements shall be carried out at steady state conditions with at least 3 different \( \Delta T \): 6° ± 1° K, 8°± 1° K, 10° ± 1° K for each flow rate.

The measurements were carried out with at least 20 recordings under steady state conditions. For the internal heat supply method the temperature of the test room's inner walls, floor and ceiling shall be...
controlled and maintained uniform at any level necessary to maintain a maximum temperature difference between these surfaces and the air on coil temperature of less than 1.0 K during the measurements. The probes placed on the beams are shown in Figure 7.

Also a humidifier was monitored and controlled along the process to calculate the latent heat shown Figure 8.

Results

The cooling capacity of the beams were calculated from the equation:

$$P = \dot{m} \cdot c_p \cdot \Delta T_w$$

(1)

The specific cooling capacity of the chilled beams was calculated from the equation:

$$P_L = \frac{P}{L}$$

(2)

The specific cooling capacity was plotted in a diagram as a function of the temperature difference (ΔT) between the on coil temperature (reference room temperature) and the mean cooling water. This shows that as temperature difference rises, we may obtain more cooling capacity from the beams.
Results of Measurements | Measurement Points
--- | ---
Number | 1 | 2 | 3
Cooling Water flow rate |ṁ | 0,1307 kg/s
Water Inlet | T\textsubscript{in} | 15,5 °C | 17,1 °C | 19 °C
Water Outlet | T\textsubscript{out} | 17,2 °C | 18,5 °C | 19,9 °C
Globe | T\textsubscript{g} | 25,3 °C | 25,1 °C | 25,4 °C
Air - 1,7 m | T\textsubscript{a 1,7} | 25,6 °C | 25,4 °C | 25 °C
Air - 1,1 m | T\textsubscript{a 1,1} | 25,9 °C | 25,4 °C | 24,8 °C
Air - 0,1 m | T\textsubscript{a 0,1} | 25,2 °C | 24,7 °C | 24,5 °C
Surface Inside Ceiling | T\textsubscript{ceiling 1} | 24,9 °C | 24,9 °C | 24,8 °C
Air on coil | T\textsubscript{ac} | 19,8 °C | 20,6 °C | 21,2 °C
Air Temperature 0,75 m below beam | T\textsubscript{air} | 18,4 °C | 19 °C | 19,5 °C
Main air Velocity 0,75 m below beam | V\textsubscript{air} | 0,23 m/s | 0,18 m/s | 0,15 m/s
Heat Loss During Steady State | Q\textsubscript{p} | 165 W
Total Cooling Capacity | P | 928 W | 764 W | 491 W
Heating Capacity (Counter Loads) | P | 1250 W | 1000 W | 750 W

Table 2. Measurements of the Beams

Accordingly, the chilled beam devices established in a test room, performed for cooling in summer conditions. The needed heat gain was provided by counter loads placed in three different points in the room. Tests were accomplished when the room temperature stays in steady state conditions in 5 minutes and measured 20 times during this condition.
<table>
<thead>
<tr>
<th>Calculations on Measurements</th>
<th>Measuring point</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>1</td>
</tr>
<tr>
<td>Reference Temperature $T_{ac}$</td>
<td>25,3 °C</td>
</tr>
<tr>
<td>Water temperature rise $\Delta T_w$</td>
<td>1,7 K</td>
</tr>
<tr>
<td>reference - water mean $\Delta T$</td>
<td>9,8 K</td>
</tr>
<tr>
<td>specific; test room area $P_{ht}$</td>
<td>-61,8 W/m²</td>
</tr>
<tr>
<td>specific; total length $P_{lt}$</td>
<td>-343,7 W/m</td>
</tr>
<tr>
<td>specific; active length $P_l$</td>
<td>-386 W/m</td>
</tr>
<tr>
<td>total $P$</td>
<td>-928 W</td>
</tr>
<tr>
<td>Heat transfer test room periphery $P_t$</td>
<td>-160 W</td>
</tr>
<tr>
<td>Heat balance $\Delta P$</td>
<td>-162 W</td>
</tr>
</tbody>
</table>

Table 3. Specific and total capacities

![Figure 9. Cooling Capacity Range with respect to temperature difference](image-url)
References

REHVA, Federation of European Heating, Ventilation and Air-conditioning Associations, – Chilled Beam Application Guidebook