ANALYSIS OF CHILLED CEILING PERFORMANCE TO CONTROL TEMPERATURE IN A DATA CONTROL CENTER USING ENERGYPLUS: A CASE STUDY

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ABSTRACT

Context: The case study presented here was carried out to assist the designers in making a decision about the use of chilled ceiling panels coupled with an air handling unit in a data center with limited usable ceiling area. **Project Description:** A continually operational data control center, located on the sixth floor of a triangular-shaped building was used for this study. The building is located in Frankfurt, Germany. The tenants requested a constant 22°C operative temperature for the space while the outside air temperature is below 26°C. The manufacturer of the chilled ceiling panels was only able to supply the panels in a certain shape. This meant that only part of the ceiling could be covered with panels. An energy model was used to evaluate the performance of the chilled ceiling panels and any additional need for cooling. **Approach:** OpenStudio plugin for SketchUp and EnergyPlus™ were used to generate the energy model. The weather file: DEU_Frankfurt.am.Main.106370_ IWEC provided by the office of Energy Efficiency and Renewable Energy (EERE) of the US Department of Energy was used to obtain the outdoor air temperatures and solar radiation impact on the building. The zone operative temperatures from the simulation results were then analyzed. The tenant provided the zone operative temperature requirement in relation to the outdoor air temperature. The study checked the number of hours that the operational temperature requirement was not met (unmet hours) and the number of degree hours (°C) that the average hourly operative temperature exceeded the requirement (unmet degree hours). The results had to be acceptable according to the German Institute of Standardization requirements as per the DIN-4108-2 standard. This project is an interesting case study where the designers relied on the results from the simulation to make informed decisions for their final design and to validate it to the tenant.

INTRODUCTION

Research indicates that an average person in industrialized countries spends about 90% of his/her time indoors. (Höppe, 2002) This indicates the importance of indoor environmental control. Although individual preferences may vary, designers aim to satisfy the requirements of a majority of the occupants. Designers constantly strive to achieve acceptable human thermal comfort conditions in the spaces that they design.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 55-2004 defines thermal comfort based on six factors:

- Metabolic rate
- Clothing insulation
- Mean air temperature
- Mean radiant temperature
- Air change rate
- Humidity

Slight changes in indoor environmental conditions can affect human comfort significantly. Research establishes that traditional displacement systems coupled with hydronic radiant cooling systems provide superior conditions for human comfort compared to all-air systems by reducing undesirable air movement. (Feustel, et al., 1995) ASHRAE standard 55-2004 recommends reporting the rate change of operational temperatures to evaluate the thermal conditions of a space. The standard defines operational temperature as:

"The average of the air temperature and the mean radiant temperature weighted, respectively, by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant."

The German Sustainable Building Council (DGNB) system criterion 18 (Thermal comfort in winter) and criterion 19 (Thermal comfort in summer) evaluate the thermal comfort based on:

- Operative temperature
- Drafts
- Floor surface temperature and radiant temperature asymmetry
- Relative humidity
- Vertical temperature gradient

The project team considered both these standards for assessing the thermal comfort conditions. The energy model was used to validate the fulfillment of operative temperature requirements to improve occupant thermal comfort.

PROJECT DETAILS

Energy Conservation Measures in the Project

The project team is aiming for a LEED® Gold rating, which makes energy efficiency a priority in the design. Several energy efficient measures (EEMs) were adopted to achieve this. EEMs include but are not limited to:

High Quality Envelope: The U-value of the external walls is 0.15 W/m2. The building also has double-pane aluminum frame windows with a U-value of 1.20 and their solar heat gain coefficient is 0.60.

Direct Outdoor Air System with Heat Recovery: The supply air is pre-heated by the heat recovered from return air. This considerably reduces the energy required for heating.

Natural Ventilation: The building has six atriums that house winter gardens and utilize natural ventilation to maintain a satisfying temperature range for most parts of the year.

Automated Shading: Automatically controlled louvers are used for all the windows (except the atriums) to reduce the radiant heat gain during summers. Daylight control considerably reduces lighting loads in most office spaces. This also significantly improves the visual quality of the interior spaces.

Occupancy Sensors: Circulation spaces are equipped with occupancy sensors to minimize unnecessary waste of electricity for lighting and reduce the thermal load on the system feeding into the zone.

District Heating: The heating energy source for this project is district heating. The district heating service provider has a primary energy factor of 0.54.

Hydronic Heating and Cooling: Hydronic systems require lower hot water temperatures and higher cold-water temperatures than traditional all-air systems. They also reduce the electric load requirements of the building by eliminating or reducing the use of supply fans (Tian, et al., 2005).

Fig. 1 shows the image of the geometry created in the OpenStudio plugin for SketchUp and table 1 presents a summary of the building design.

Table 1
Building Design Summary

Mechanical Ventilation system	Direct outdoor air system
Heating and Components	Chilled ceilings and Radiators
Above Grade walls	U-Value = 0.15 W/m2
Windows	U-Value = 1.20 W/m2 Solar Heat Gain Coefficient = 0.60

Figure 1: Geometry of the Energy Model in the OpenStudio Plugin for SketchUp

Data Center

The sixth level of the building accommodates a data center with constant internal thermal loads. The tenant requested a constant operative temperature of 22°C while the outside air temperature remains below 26°C for this space. Table 2 presents information related to these zones.

Table 2
Internal Loads of the Data Center on Level 6

Lighting Load	15.9 W/m2
Equipment Load	24.7 W/m2
Occupancy	20 people
Outdoor Air Flow Rate	0.25 m3/s
Supply Air Temperature	18 °C

Orientation

The building is triangular in shape and split into three “wings”. The triangular shape of the building exposes each side to a different solar orientation. The entire floor plan is divided into three distinct areas that are separated by eight-story high atria. Wing C is oriented towards the North, Wing A towards the East and Wing B towards the Southwest.

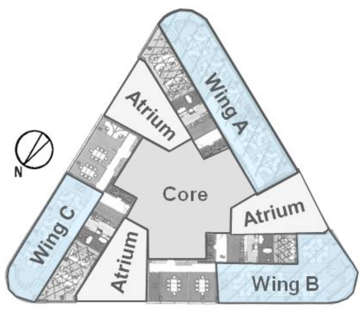

Figure 2: Zoning Plan for the 6th Level

Frankfurt Weather

The weather data provided by the EERE of the US Department of Energy was used for the energy model. ASHRAE classifies Frankfurt as climate zone 5c. Frankfurt receives rain during most of the year and is moderately humid throughout the year. The winters are warm and cloudy. The 0.4% cooling design temperatures are:

Dry Bulb Temperature – 30.4 °C

Wet Bulb Temperature – 20.5 °C

Fig.3 displays the annual average daily outdoor dry bulb and wet bulb temperatures for Frankfurt according to the weather file that was used for simulation.

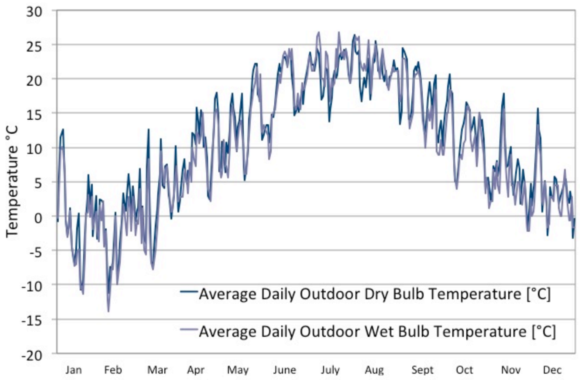

Figure 3: Average Daily Dry Bulb and Wet Bulb Temperatures for Frankfurt

RADIANT CEILING PANELS

Literature Review

Crucial components and considerations for the use of chilled radiant panels in a space were studied under three categories:

Human Comfort:

Conventional all-air systems result in spots of localized hot / cold air that can result in draft air movement. This causes unwarranted cooling for humans, affecting their comfort conditions according to Corgnati, et al. (2009). Corgnati, et al. performed a numerical analysis of chilled ceiling panels coupled with air systems for the conditioning of office spaces. Their analysis showed considerable reduction of draft air movement and improved comfort. This observation was also substantiated by an experimental setup.

Energy Efficiency:

Conroy, et al. (2001) state that the combination of radiant panels and air systems is more energy efficient than all air systems. However, the energy efficiency is achieved only by adopting an optimized control strategy; Tian, et al. (2005) compared the energy usage of a typical VAV system and a radiant system to validate this. Their research states that the radiant systems have an edge over all air systems in energy conservation only due to reduced fan energy consumption.

Radiant Panel Performance:

Condensation on the chilled panel surface is a major concern that limits their use in several climatic regions. Dew point temperature inside a conditioned space can be controlled to eliminate this problem according to Conroy, et al. (2001). The cooling capacity of the chilled ceiling is also dependent on the prevalent zone conditions. Jeong, et al. (2003) noticed a slight increase in the cooling capacity of the chilled ceiling panels by a 5% to 35% increase in supply air flowrate. The optimization of the air system was done at an earlier stage for this project. Therefore, this background information was not explicitly used in the energy model inputs.

Modeling the Chilled Ceiling Panels

Chantrasrisalai, et al. (1995) studied the modeling of low-temperature radiant systems in EnergyPlus™ and listed the parameters that the model is most sensitive to. According to their study, low-temperature radiant systems modeling results vary greatly by changing the following parameters:

- Thermal properties of the building materials
- System operation schedule
- System setpoint temperatures
- Schedules of the zone internal gains

Their study also pointed towards the importance of comparing energy performance to the comfort parameters to evaluate various components.

For this study, the modeling inputs were carefully assessed from the manufacturer information and each functional component was checked against the thermal comfort and weather conditions at various stages.

Table 3 lists the chilled ceiling panel specifications from the manufacturer.

Table 3
Specifications of the Chilled Ceiling Panels

Overall Size	1.25 m x 3.2 m
Hydronic Tube Inside Diameter	8mm
Supply Water Temperature	15 °C
Return Water Temperature	18 °C
Zone Temperature	22 °C
Operation Schedule	24 hours a day

Geometry of the Chilled Ceiling Panels

The manufacturer specified a panel size of 3.2m x 1.25m for the chilled ceiling panels. The initial simulation results considered the entire ceiling area to be active. However, the panel size limitations and the triangular shape of the building reduced the coverage. The tenant was concerned about the thermal comfort in the corner offices, due to higher internal loads and reduced chilled ceiling area. It was important to draw the exact layout of the chilled ceiling panels in the model to estimate their cooling capacity.

Inputs for the EnergyPlus Model

ZoneHVAC:LowTemperatureRadiant:VariableFlow: component in EnergyPlus™ was used to model the chilled ceiling panels. Fig. 4 shows a screenshot of the inputs required to model this component in EnergyPlus™. It was important to fill each of these fields with precise manufacturer data for accuracy. The study only considered the cooling mode of the radiant ceiling panels.

Field	Units
Name	
Availability Schedule Name	
Zone Name	
Surface Name or Radiant Surface Group Name	
Hydronic Tubing Inside Diameter	m
Hydronic Tubing Length	m
Temperature Control Type	
Maximum Hot Water Flow	m3/s
Heating Water Inlet Node Name	
Heating Water Outlet Node Name	
Heating Control Throttling Range	deltaC
Heating Control Temperature Schedule Name	
Maximum Cold Water Flow	m3/s
Cooling Water Inlet Node Name	
Cooling Water Outlet Node Name	
Cooling Control Throttling Range	deltaC
Cooling Control Temperature Schedule Name	
Condensation Control Type	
Condensation Control Dewpoint Offset	C

Figure 4: Screenshot of ZoneHVAC:LowTemperatureRadiant:VariableFlow EnergyPlus™ Component Inputs

Surface Name or Radiant Surface Group Name:

The surface group contains all the sub-surfaces drawn in the geometry to define the panels.

Hydronic Tubing Inside Diameter:

This critical input taken from manufacturer specifications specifies the inside diameter of the piping used in the ceiling panels.

Hydronic Tubing Length:

This is the length of the tubing through all the panels in the surface group. It is calculated from the manufactures specifications of panel size and tube spacing.

Temperature Control Type:

Zone thermostats were chosen to control the chilled ceiling panels for this project. The ceilings request water when the thermostat requirements are not met within the zone.

Maximum Cold Water Flow:

To size the ceiling panels correctly the mass flow rate of the water through the entire ceiling must be calculated. The flow rate of the water is calculated using the capacity of each unit (W/m²) and the delta T of the water as it passes through the panel, this value is then entered into this field.

Cooling Control Throttle Range and the Cooling Control Temperature Schedule Name:

EnergyPlus input-output reference defines this to be the range over which the system fluctuates to achieve the maximum water flow rate. This specifies the response of the radiant panel system to the mean zone air temperature.

METHODOLOGY

Orientation Study

Due to the nature of the building and its symmetry, only one wing of the building was modeled. This wing was simulated in three orientations to represent the three wings of the building. Table 4 displays the unmet occupied hours and the unmet degree hours for these three orientations.

Table 4
Results from Parametric Study

Wing and Orientation	Unmet Occupied Hours	Unmet Degree Hours
Wing A - East	5251	5227
Wing B - Southwest	5436	5831
Wing C - North	5340	5675

The orientation study established the Southwest wing (Wing B) to have the highest unmet degree hours. It is assumed that if Wing B (Southwest orientation) can meet its comfort criteria then the other two wings will also meet their comfort criteria. Only Wing B (Southwest orientation) was studied from here.

Supplementary Cooling

The orientation study was conducted on the wings conditioned only by chilled ceiling panels. The unmet degree hours for all three wings were unsatisfactory from the orientation study and hence supplementary cooling was provided to the spaces to achieve the tenant specified set points. Table 5 lists the chilled ceiling panel design information used for conditioning wing B for the orientation study.

Table 5
Chilled Ceiling Design Information for Wing B

Total ceiling area of Wing B	218 m^2
Area of Chilled ceiling panels	148 m^2 (37 nos.)
% Coverage of chilled ceiling panels	68%
Total Cooling capacity of chilled ceilings	13.17 kW

Fan coil units and chilled beams were two alternative sources of cooling suggested to the tenant. Chilled beams were preferred over fan coil units as they provide better thermal comfort owing to lower airflow rates and a larger number of these units create uniformity in the air temperature. The chilled ceiling panel area was reduced by 10 m^2 in the model to account for the space requirements to fix the chilled beam units. Table 6 lists the design information of chilled beams used for conditioning wing B.

Table 6
Chilled Beams Design Information for Wing B

Occupancy Load	20 people
Lighting Load	15.9 W/m^2
Equipment Load	24.7 W/m^2
Number of Chilled Beam units	30 nos.
Cooling capacity of Chilled Beams	7.5 kW
Reduced Chilled ceiling panel area	10 m^2
Reduced Chilled ceiling panel cooling capacity	0.48 kW

RESULTS AND DISCUSSION

The aim of the project team was to achieve the tenant specified setpoint for the zone operative temperature. Fig. 5 illustrates the results from the iteration when just chilled ceiling panels condition the zones.

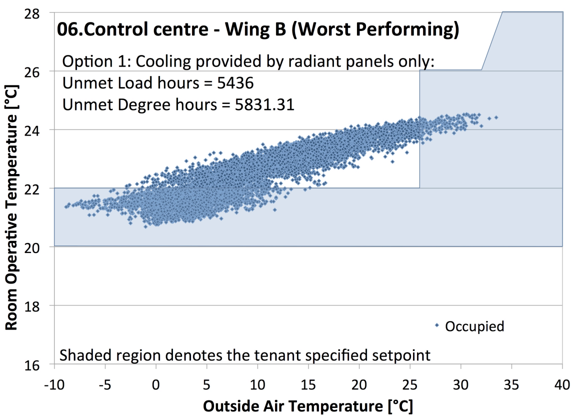

Figure 5: Plot of Zone Operative Temperature vs. Outdoor Air Temperature (no fan coil unit)

Each point in the graph represents the average operative temperature of each hour during the year plotted against the outdoor air temperature. The shaded region in the graphs represents the tenant specified operative temperature setpoint. The project also aimed to meet the German Institute of Standardization (DIN) requirements for the number of unmet degree hours. The DIN-4108/2 standard for thermal protection and energy economy of buildings requires the unmet degree hours for the chosen setpoint to be less than 400. Since the radiant panels could not meet the requirements, additional cooling was provided by adding a fan coil unit. Fig. 6 shows the results from this iteration.

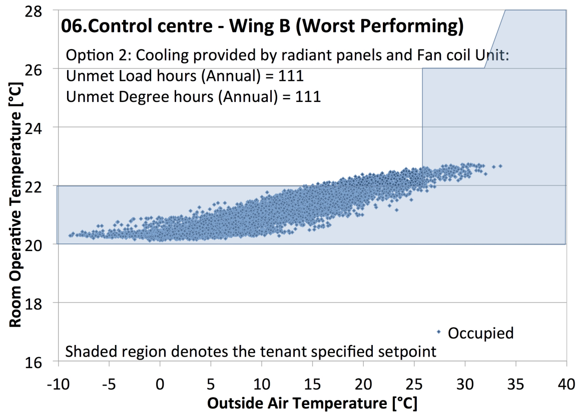

Figure 6: Plot of Zone Operative Temperature vs. Outdoor Air Temperature (with radiant cooling and fan coil unit)

The capacity of the fan coil unit was optimized through an iterative modeling process. It was found that around 4kW of extra cooling capacity was required for these spaces. Once the designers were aware of the need for extra cooling and the capacity required, they looked at alternative solutions to the fan coil. To keep the temperatures even and air flows low, they chose to fulfill this extra capacity by the using chilled beams. A total of 12 chilled beam units with an additional 7.5 kW cooling capacity were added to Wing B to meet this requirement for extra cooling. Fig. 7 illustrates the results of the iteration with chilled ceiling panels and chilled beams.

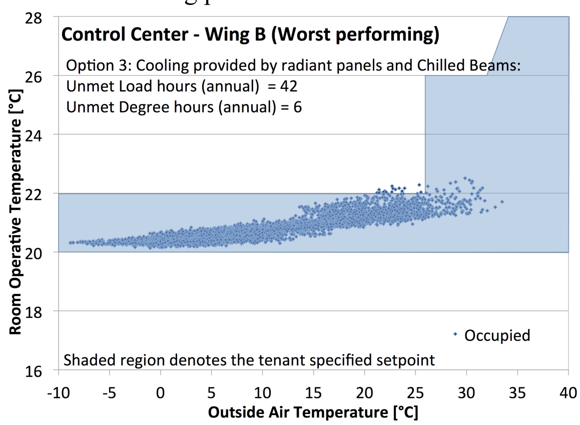

Figure 7: Plot of Zone Operative Temperature vs. Outdoor Air Temperature (with radiant cooling and chilled beams)

This iterative study was crucial for the designers to know that the space required additional cooling and to calculate the additional capacity of cooling required. The designers used the results from this study to improve the thermal comfort within the space by using chilled beams with greater cooling capacity. The total unmet load hours, unmet degree hours and the additional cooling capacities for the iterations are listed in Table 7.

Table 7
Results for Unmet Load Hours and Degree Hours

Option	**Additional Cooling Capacity**	**Unmet Load Hours**	**Unmet Degree Hours**
Only Radiant Cooling	0 kW	5436	5831.31
Radiant Cooling with Fan Coil Unit	4 kW	111	111
Radiant Cooling with Chilled Beams	7.5 kW	42	6

CONCLUSION

Energy models provide a basis for design decisions. Generating a model was very important to achieve the tenant operative temperature requirements in this case study. The results served a dual purpose of assisting the designers and convincing the tenant about the validity of the design.

Practical issues that were identified by the manufacturer were successfully included in the model to find a suitable solution. Constant scrutiny of component functioning against the zone thermal conditions and the weather conditions was the key factor to ensure accuracy of the energy model. Metered data from the actual building after it starts functioning would further verify this model and results.

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