1. BACKGROUND

For the week of July 19-23, 2010 members from CBE traveled to the California State Teachers Retirement System (CalSTRS) building in Sacramento with two main goals in mind: (1) help validate the CBE UFAD design tool with measured building data and (2) evaluate the performance of the CalSTRS UFAD system during different blinds setting scenarios (open, horizontal, and closed). During certain times of year, CalSTRS building engineers have had trouble meeting setpoints because of solar loading. Two spaces were monitored: (1) a conference room on the 3rd floor and (2) an open plan space on the 11th floor.

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2. METHODS

Third floor conference room

In the 3rd floor conference room, pressure measurements were taken to determine the leakage between the isolated plenum space of the conference room and adjacent rooms and plenums. Swirl diffusers were covered and bar grille diffusers were disconnected from ducts to simulate actual plenum environment. Air flow was measured from each bar grille diffuser and correlated with plenum pressure. Wireless temperature sensing motes (wireless devices associated with the CBE portable measurement cart) were deployed in three diffusers, as well as the supply air entrance into the conference room and the supply air exit from a duct into the plenum space. Temperature stratification and plenum pressure were recorded each day and evening by the portable measurement cart. One pyranometer was setup on the bottom window sill in the southwest corner of the conference room to record transmitted solar radiation. Another pyranometer was setup on the roof to record environmental solar radiation for the entire testing period. The rooftop pyranometer malfunctioned, so data is only available from the 3rd floor pyranometer. Two days of testing were done with blinds up and one day of testing was done with blinds closed. An infrared gun was used to measure the temperature of the floor with and without direct sunlight.

11th floor open plan space
In the 11th floor open plan office space, plenum pressure was measured with both the portable cart and a wireless mote connected to a pressure sensor. Wireless motes were placed in swirl diffusers throughout the southeast plenum section of the open plan space and at the two ducts that supply the plenum to evaluate thermal decay in the plenum. One wireless stratification tree was placed on the interior and one was placed near the perimeter to record temperature stratification in addition to the cart measurements. The portable cart was moved to various locations within the open plan space to evaluate the stratification of the space. One day of testing was done with blinds in the horizontal position and one day with the blinds open.

3. RESULTS

UFAD temperature performance

Thermal stratification was measured on both the third and eleventh floors using the portable measurement cart in order to assess the effect of blind position on thermal comfort and the ability of the UFAD system to satisfy the cooling load. UFAD systems are commonly controlled using a thermostat mounted at a 4 ft height. If significant stratification develops, the occupied zone (OZ) defined as the vertical region from 4 inches to 67 inches from the floor) may end up being too cool and cause discomfort. The degree of stratification is gauged by the difference between the temperatures at 67 and 4 inches (namely the head-foot temperature difference). We generally consider stratification optimal when it is in the range of 2 to 4°F. As a single value, stratification serves as a good indicator of UFAD performance, though the full stratification profile (air temperature at thirteen room heights) provides a clearer picture of UFAD temperature performance.

Third floor conference room

Figure 1 shows the room air stratification profiles for the third floor conference room during two different times (8:00am and 11:00am) and blinds positions (open and closed). The solid lines represent the 8:00am measurements and the dotted lines represent the 11:00am measurements. The red lines refer to the “blinds closed” scenario and the blue lines refer to the “blinds open” scenario.
Figure 1: Thermal stratification profiles for blinds scenarios in third floor conference room

There are multiple points of interest in this chart that are discussed in the sections that follow.

**Blinds position effect on room temperature**

The stratification profiles for the “blinds open” scenario are warmer than the stratification profiles for the “blinds closed” scenario, indicating a small cooling effect of the blinds (~0.6 – 1.2°C). Figure 2 shows the solar load entering the room as measured by a pyranometer that was placed on a southeast window sill (unaffected by blinds position). The solar load on the space was nearly identical on the two days of interest (7/22 and 7/23); the small difference at the peak we assume has negligible impact on the results. This suggests that the cooling effect observed was related to the blinds position. The peak solar load occurred at ~9:30am on both days but there was little direct solar gain due to the orientation of the glazed walls.

The blue/red circles and triangles in Figure 1 represent the average occupied zone temperatures for the corresponding scenarios, and the green circle represents the space setpoint (73°F). The measurements indicate that the space is cooler than setpoint at 8:00am and that by 11:00am the system is unable to meet setpoint. As noted by the facilities managers, the evening purge needed adjustment in order to prevent the necessity of a morning heating period.
Blinds position effect on fan terminal unit airflow

Figure 3 shows building management system (BMS) data (fan terminal unit command airflow, space temperature, setpoint, and supply air temperature) for the corresponding two-day time period. Supply air temperature (SAT) (FTU discharge temperature in BMS) and setpoint are only shown for the occupied time in order to reduce clutter on the chart and enhance clarity. The full two day trends of SAT and setpoint are shown in Figure 4.

Despite the slight cooling effect associated with closed blinds, we do not see an associated reduction in fan energy during the occupied hours of the day when the system is operational. The fan terminal unit operates the same amount of time above its minimum setting during the closed blinds scenario and the open blinds scenario (8.5 hours). However, the relationship between fan terminal unit energy and blinds position is confounded by the differing supply air temperature behaviors between the two days. During the blinds open day, the supply air temperature drops from 69°F to 65°F starting at 3:00PM while the same drop in supply air temperature happens at 4:15PM on the blinds closed day. This appears to be the result of AHU SAT resetting.
Figure 4 shows space, supply, and setpoint temperatures for the corresponding two day period. The early morning of 7/22 is characterized by spikes in the supply air temperature that correspond to working out kinks in the morning warmup routine. Because the conference room is located in the southeast corner of the building, the solar load peaks in morning and there is no direct sun in the afternoon. The supply air temperature drops from 69°F to 65°F between 3:00-6:00PM, which in combination with the high airflow, leads to overcooling in the afternoon, at least for this zone (the supply air reset could be activated by other factors outside of this zone). This whole sequence is complicated by multiple changes occurring at the same time and the fact that the box is undersized (or maximum flow settings are too low) resulting in loss of room temperature control in the early part of the day. Then in the latter part of the day when the room temperature drops, the box airflow does not reduce fast enough to account for the rapidly decreasing room temperature that is occurring due to the combined effect of the lower SAT and box high (but decreasing) airflow. This situation could be mitigated by better sizing of the boxes and tuning of the controls to respond more rapidly to effects such as the SAT reset. Perhaps the AHU SAT reset is also too aggressive. The setpoint temperature (red-dotted line) currently follows a traditional setback routine (73°F occupied times and 75°F unoccupied times). We recommend raising the setpoint to 75°F along with the previous suggestions to gain control of the zone. Additionally, the room setpoint steps down to 73°F from 1:40AM – 2:15AM, which is likely a programming mistake, which is accompanied by an unnecessary drop in supply air temperature.
Due to the inconsistency in supply air temperature behavior, and the fact the zone is not being controlled well for much of the day, we are unable to assess the effect of blinds position on fan box energy consumption over the course of the day. However, it is clear from the data that when the blinds are closed the load is lower in the room resulting in lower room temperatures. This is consistent with our hypothesis that the solar gain is concentrated at the windows and doesn’t enter the space itself. Simulations have shown that for mixed systems (normal overhead VAV) the overall load is the same when low-e windows are used, but for UFAD systems there is greater stratification near the windows so the solar load is “siphoned” up to the ceiling thus reducing the impact on the zone load. This behavior is clearly shown by the large increase in temperature at the top of the profile when blinds are closed. The reason for the odd shape of the 11:00am profiles is not clear. It suggests that the measurement tree is being impacted by some factor; this sometimes occurs when airflow from the diffusers bounces off the ceiling, lowering the temperature in the upper part. (See below).

Blinds position effect on stratification profile shape

The stratification profiles in Figure 1 follow a fairly normal shape during the 8:00am measurements, but follow a less ideal stratification profile during the 11:00am measurements, with the stratification deteriorating near the top of the occupied zone (57°). Figure 5 shows 11:00am measurements compared to 12:00pm measurements. While the “blinds open” profiles are very similar, the “blinds closed” 12:00pm profile shows a further deterioration of stratification. The air temperature four inches from the ceiling is colder than the air temperature in the occupied zone. This profile suggests that cold air from the perimeter diffusers is being thrown with sufficient velocity to reach the ceiling, creating a mixed-air environment rather than a stratified environment. The deterioration of stratification related to airflow can clearly be seen.
in Figure 6, which displays trends for thermal stratification and the corresponding command airflow. Reducing the maximum airflows of the perimeter fan terminal units would help prevent this stratification degradation, but may also affect the ability of the system to control to setpoint. Additionally, raising the setpoint would reduce the amount of time the fan terminal unit is at maximum airflow, which would improve stratification.

The behavior demonstrated in these tests highlights the dilemma with UFAD systems. Unless the units are sized for high SATs they will not be able to meet the load and the high airflow compromises the stratification further aggravating control of the space load. These affects can be ameliorated by either installing more (or different, low throw) diffusers or by lowering AHU SAT. However, lowering AHU SAT tends to end up overcooling the interior spaces. Raising the space setpoint would help all of these issues.

Figure 5: Thermal stratification profiles for blinds scenarios in third floor conference room
Figure 6: Thermal stratification trends and command airflow for blinds closed scenario

11th floor open plan space

Blinds position effect on room temperature

Figure 7 shows the average stratification profiles for the hour-long measurement period on each of the two blinds case scenarios (horizontal and open). The profiles are very close to each other, indicating that the system is controlling well and the blinds position is not affecting the temperature in the space. Further discussion of this finding can be found in the section: Blinds position effect on fan terminal unit airflow.
The stratification profiles for this space were consistent with expectations of a well-performing UFAD system. Figure 8 provides a graphical summary of the performance of the UFAD system in the 11th floor open plan space. The chart plots average room air temperature stratification against the average occupied zone air temperature for each location measured on the 11th floor on two days of testing (blinds open and blinds horizontal). There are two shaded areas representing different “comfort zones.” The beige shaded area represents the comfort zone as determined by the CBE comfort modeling study. The pink shaded area represents the comfort zone as determined by ASHRAE Standard 55. The ASHRAE comfort zone was determined from operational and occupant parameters based on ASHRAE standard comfort zone models. In this case, we assumed a Metabolic value = 1.2, Clothing value = 0.6, Relative Humidity = 50%, and Velocity at the occupant <50 fpm.

All points fall within the two comfort zones and most points fall within the CBE Comfort Model zone, which we feel provides a more accurate picture of comfortable conditions. There is little variability in both stratification and occupied zone temperature, indicating good control of the open plan space to setpoint (73°F). The occupied zone temperatures fall on the colder side of the comfort zone, indicating potential to raise the setpoint for energy savings.

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Blinds position effect on fan terminal unit airflow

Figure 9 shows the BMS data for fan terminal unit airflow and space temperature in the southeast corner of the 11th floor open plan space. The chart plots two days of data, corresponding to the open and horizontal blinds scenarios. The chart shows a 1.5 hour difference in time the fan terminal unit spent above its minimum airflow rate between the blinds horizontal (9.5 hours) and blinds open (11 hours) scenarios. As in the third floor results however, the supply air temperature inconsistencies between the two days of measurement prevent us from drawing any conclusion concerning blinds position and fan terminal unit energy. It is likely the difference in fan operating hours results from the difference in time when the SAT is reset; later reduction (blinds open) results in longer operating time for the fan coil unit. As is the case for the 3rd floor, the units seem undersized for the AHU SAT being used and the room setpoint seems too high.
Figure 9: Building management system data for 11th floor open plan space

Thermal decay

Figure 10 is an illustrated thermal contour map for the eleventh-floor southern zone underfloor plenum. The white dots represent wireless mote locations where temperatures were taken. The temperatures shown in Figure 10 represent the average temperature over the course of a half-hour measurement period. Temperatures were linearly interpolated to provide a contour map.

Thermal decay depends on airflow rate and temperature distribution caused by how the supply airflow is delivered to the plenum. Temperatures are typically dictated by how long the air has to travel (while picking up heat) to a particular location.

Unfortunately, a software bug led to data collection problems with the majority of the wireless motes, leading to a very limited data set. Without data to fill out the larger measurement area, we are unable to draw conclusions regarding thermal decay in the plenum. However, the small dataset does provide a picture of underfloor decay for this section of the 11th floor and suggests a maximum of 4°F decay in this small area. Further study is warranted to analyze how thermal decay may factor into the ability of the system to meet setpoint in the space.
Multi-path leakage test

In the 3rd floor conference room, air leakage was measured to areas adjacent to the underfloor plenum, including to the room (Category 2 leakage), to the adjacent underfloor plenums, to the floor below, directly to the return plenum, and to outside the building. The purpose of this multi-path leakage test is to simultaneously characterize airflow rates through all major leakage pathways from the underfloor plenum. The accuracy of this test method has been demonstrated at a few other buildings during the last few years.

Multi-path leakage test method

In the single zone leakage methods usually employed leakage is determined assuming all the leaks have the same pressure:

\[ Q = k \Delta P^n \]

(1)

Where:

- \( Q \) is the leakage airflow rate (cfm)
- \( \Delta P \) is the pressure across the leakage pathway (iwc, or Pa)
- \( k \) and \( n \) are regression coefficients (0.5<=n<=1)
The Multi-Path approach uses a more realistic model of leakage from the underfloor plenum by measuring and determining the air leakage correlation for each major leakage pathway. Rather than limiting our attention and measurements to only the pressure difference between the plenum and room (leaving other pathways poorly determined), this measurement technique provides greater detail by modeling the total leakage from the underfloor plenum as the sum of several right hand terms from Equation (1) each representing the leakage through a major pathway. In the case of our tests in the CalSTRS building, we used the following equation:

\[
Q = k_1 \Delta P_1^{n_1} + k_2 \Delta P_2^{n_2} + k_3 \Delta P_3^{n_3} + k_4 \Delta P_4^{n_4} + k_5 \Delta P_5^{n_5} + k_6 \Delta P_6^{n_6} + k_7 \Delta P_7^{n_7}
\]  

(2)

Where:

- \(k_i \Delta P_i^{n_i}\) is the leakage contribution from each of the following four pathways:
  - \(i = 1\), room through all openings (Category 2 Leakage)
  - \(i = 2\), adjacent plenum to the North
  - \(i = 3\), adjacent plenum to the West
  - \(i = 4\), the floor below (the atrium)
  - \(i = 5\), the return plenum above the room
  - \(i = 6\), the outside
  - \(i = 7\), the perimeter duct system (not a leakage path in normal operating modes)

For Equation (2) to be used successfully, the pressure differences governing the various pathways must be independently changed and sufficient data points taken to yield a good regression. Although it would be desirable to be able to hold one pressure (for example, the plenum/room pressure difference) constant, it is not necessary to do this as long as enough data points are collected. It is also quite difficult to do this in practice using a building’s control system. In the CalSTRS building, we used the BMS controls to adjust the pressure in the adjacent underfloors plenums, the supply flow (and thus pressure) to the floor below, and the speed of the return fan to change the return plenum pressure, and a “Blower Door” to vary the pressure in the room (and its return plenum) in various combinations to allow a range of differential pressures to be obtained for each leakage pathway. In the case of the outside, natural fluctuations in wind speed and direction provided the necessary pressure variations.

The advantage of the multi-path leakage test is that by developing a unique correlation for the leakage from the plenum to all openings, it can accurately predict true Category 2 leakage as a function of pressure difference.

In many instances the flow exponent “\(n\)” is difficult to determine and a single “\(n\)” can be used from the measurement of “total leakage”. At CalSTRS, sufficient measurements were taken to be able to independently determine each flow exponent.

Prior to our leakage tests we found and fixed a large hole (about 6 inches in diameter) between the underfloor plenums. There may have been other similar penetrations that could be easily sealed which we did not find.

**Leakage results**
Initial analysis showed no or very little correlation of underfloor pressure with changes to the pressure of the floor below or to outside, thus these paths were eliminated. Table 1 shows the regression coefficients, normal operating pressures and resulting leakage flows. Note that leakage to/from adjacent underfloor plenums likely still serves an occupied zone, just not the 3rd floor conference room. Only about 3% of the total supply flow does not go to an occupied zone.

Table 1: Leakage and normal operating pressures and flows of leak paths to the 3rd floor conference room underfloor plenum. Normal operating pressures are for 11 AM to 2 PM on July 20-23, 2010. The flow into the 3rd floor conference room UF plenum was 2000 cfm (command by the BMS system).

<table>
<thead>
<tr>
<th>Leakage Path</th>
<th>Flow coefficient (k) (for flow in cfm)</th>
<th>Flow exponent (n)</th>
<th>Normal operating pressure (Pascals)</th>
<th>Normal operating flow (cfm)</th>
<th>% of Normal operating flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>10.88</td>
<td>.545</td>
<td>15.0</td>
<td>48.2</td>
<td>2.4</td>
</tr>
<tr>
<td>North UF Plenum</td>
<td>37.47</td>
<td>.500</td>
<td>13.8</td>
<td>138.9</td>
<td>6.9</td>
</tr>
<tr>
<td>West UF Plenum</td>
<td>0.67</td>
<td>1.000</td>
<td>14.8</td>
<td>9.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Floor below</td>
<td>0 (forced)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0</td>
</tr>
<tr>
<td>Return Plenum</td>
<td>11.79</td>
<td>.568</td>
<td>17.3</td>
<td>57.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Outside</td>
<td>0 (forced)</td>
<td>N/A</td>
<td>N/A</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Perimeter Duct</td>
<td>5.95</td>
<td>.852</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Total Leakage</td>
<td></td>
<td></td>
<td></td>
<td>12.7</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11 shows time series data for these flows during normal operating conditions. Negative flows indicate flow into the 3rd floor conference room underfloor plenum; positive flows are leakage from the plenum.
Figure 11: Leakage and normal operating flows. Note that a supply flow of 600 cfm is still reported by the BMS even during periods when the fan must be off (as indicated by the leakage to room going to zero).

Leakage to the conference room is relatively small (2.4% of the delivered air) compared to other measurements of Category II leakage. Leakage between the underfloor plenum and its return plenum in the drop ceiling above the room, presumably via walls and any existing chases has not been measured before and is a bit of a surprise. The primary leakage path is from the underfloor plenum to another underfloor plenum. At about 150 cfm during normal occupied operating conditions, this leakage is unlikely to lead to significant energy inefficiency or comfort problems in the adjacent rooms, but does lower the effective capacity of the cooling delivered to the conference room by about 7%.

4. CONCLUSIONS AND RECOMMENDATIONS

Third floor conference room

Our cart measurement results indicate that having the blinds closed has a slight cooling effect compared to having the blinds all the way open. While this cooler room air temperature was noted throughout the morning of testing, we are unable to draw conclusions from fan terminal unit operation due to inconsistencies in supply air temperature behavior between the two testing days and because the terminal units appear to be undersized for the SAT being used. Stratification profiles in the conference room indicate that the maximum airflow velocity out of the perimeter diffusers is too high, destroying stratification above 57”. More definitive results could come from
future testing where a fixed and lower supply air temperature was used along with an increased room setpoint.

Leakage in the space was measured to be relatively small and is not likely to cause comfort problems. While any leakage results in some inefficiency, our results indicate the leakage paths in the conference room are small compared to other similar scenarios we’ve tested.

11th floor open plan space

Our cart measurement results indicate that for the measured period, there is no difference in air temperature with the blinds open compared to blinds in a horizontal position. Despite initial evidence that fan terminal unit energy decreased in the horizontal blinds scenario, we were unable to draw conclusions because of inconsistencies in supply air temperature behavior between testing days.

The UFAD system is performing well, with proper levels of stratification and fairly good control to setpoint. The measured spaces were controlled to the cool end of the comfort zone, indicating potential for increased setpoints.

Future testing would provide a clearer picture of underfloor thermal decay and its effect on overall UFAD system performance.