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Publication Date
2011

Peer reviewed

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LESSONS LEARNED IN MODELING UNDERFLOOR AIR DISTRIBUTION SYSTEM

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ABSTRACT

Underfloor air distribution system (UFAD) is a mechanical air distribution strategy in which the conditioned air is primarily delivered to the zone from a pressurized plenum through floor-mounted diffusers. It has several potential advantages compared to conventional overhead (OH) mixing systems. However, most of the energy simulation programs widely used by the industry are not able to represent two distinct features of UFAD systems: room air stratification and the underfloor supply plenum. The situation has been improved with the development of a UFAD module in EnergyPlus. The Center for the Built Environment developed the modeling methods, tested them extensively, and conducted numerous studies of UFAD energy performance. This paper summarizes lessons learned related to UFAD specific issues such as thermal decay, sizing, terminal units, room air stratification and thermal comfort.

INTRODUCTION

Underfloor air distribution system (UFAD) primarily delivers the conditioned air to the zone from a pressurized plenum through floor-mounted diffusers. Compared to conventional overhead (OH) mixing systems, where the air in the zone is well- mixed, UFAD has several potential advantages such as improved thermal comfort and indoor air quality (IAQ), layout flexibility, reduced life cycle costs and improved energy efficiency in suitable climates (Bauman 2003). However, two important features of UFAD systems, which are the room air stratification and the underfloor supply plenum, could not be properly represented by most of the energy simulation programs widely used by the industry. The situation has been improved with the development of a dedicated UFAD module in EnergyPlus. (Bauman et. al. 2007), (Webster et al., 2008), (DOE, 2010). The authors have used EnergyPlus/UFAD extensively and participated in the design and implementation of refinements to the UFAD module. Through this experience many lessons have been learned on how to properly simulate these systems. These are important for design practitioners to understand to avoid pitfalls and improper assumptions. Alajmia et al. (2010) conducted the simulation study using EnergyPlus to investigate the energy benefit of UFAD compared to conventional ceiling based system. It is found that 30% of energy saving could be achieved. However, the study does not provide information on the simulation details such as how the thermal decay is addressed and how the terminal units are sized. Thermal decay might not be taken into account during the simulation. In this circumstance, the present paper summarizes the following topics that need careful consideration during the modeling process: 1) heat gains into the underfloor supply plenum, commonly referred to as thermal decay; 2) sizing and fine tuning of UFAD system components; 3) modeling terminal unit types commonly used in UFAD; 4) stratification and its implications on energy performance; 5) implications of system design and operation on thermal comfort.

SIMULATION SOFTWARE

The authors developed the office building prototype described below for development, testing, and performance studies. During this time development versions 2.1 to 6.0 of EnergyPlus software were used. Bauman et al. 2007), (Linden et al., 2009). EnergyPlus is a relatively new building energy simulation program developed under support from the U.S. Department of Energy. (DOE 2010) Based on the combination of two predecessor programs DOE-2 and BLAST, it has greater capabilities than those two as well as many other programs. Among the unique features of EnergyPlus that makes it a good platform for simulating UFAD (and other advanced technologies) are discussed in the following.

Room air stratification

Room air stratification (RAS) is a key characteristic of UFAD systems compared to conventional OH systems. Increased stratification is associated with improved energy efficiency (Linden et al., 2009) and is considered a key marker of well performing systems. To represent stratification, the room is divided into two fully mixed sub-zones as shown in Figure 1. EnergyPlus performs a heat balance on each sub-zone with the surface between the upper and lower layers in the room configured to be an “air surface” that is transparent to all radiation.

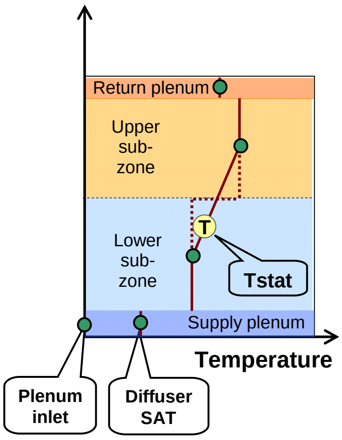

Figure 1. EnergyPlus two-layer UFAD model

There are a number of factors that influence the degree of stratification in UFAD systems and it is important that these effects be captured in UFAD modeling. Both full scale and bench scale experiments were performed to develop the stratification algorithms. Details can be found in Bauman et al. (2007), Liu and Linden (2008), Webster et al. (2008), and DOE (2010).

Thermal decay

A major barrier to modeling UFAD systems has been the inability to model supply air plenums that account for the interaction with adjacent zones and the effects of heat gain to the supply air. Thermal decay, defined as the temperature rise of the conditioned air due to convective heat gain as it travels through the underfloor supply plenum, is an important phenomena that must be taken into account in UFAD system modeling. Due to its significance, active research has been done by many researchers including Woods et al. (2008), Schiavaon et al. (2011), Bauman et al. (2006) and Schiavon et al. (2010). The authors have conducted extensive research including experimental and field studies and computational fluid dynamics (CFD) simulations to investigate the nature and impact of thermal decay; results from these studies, show that it is too important to ignore. A comprehensive description of the phenomenon and its implication has been reported by Lee et al. (2011). Unlike other energy simulation tools, EnergyPlus has the capability to model each underfloor plenum as a completely separate zone, performing all the heat, mass and energy balances to accurately simulate thermal decay. In addition, it enables the investigation of the effect of different supply plenum configurations on energy consumption.

Radiant heat transfer

EnergyPlus has the capability to perform a detailed heat balance on each surface including the effects of radiant exchange, to calculate the surface temperature in each time step,

Fully integrated solution of zone, system and plant

Unlike typical tools simulating the building loads (based on the assumed system capacity) and the HVAC system separately, EnergyPlus performs the system and plant simulation, and the air and surface heat balances simultaneously, allowing the real-time interaction among those different building components. This is important for realistic energy modeling, since the behaviour of all building components such as zone air and surfaces, chillers, fans, boilers, and pumps are highly interconnected with each other in each time step.

SIMULATION CONDITIONS

A three-story prototype office building with a rectangular shape (75 m x 51 m) and aspect ratio of 1.5 was used. The floor plate size is 3,716 m^2 (total floor area is 11,152 m^2) and each floor is composed of 4 perimeter zones, an interior zone and a service core, which represent approximately 28%, 56% and 16% of the floor area, respectively (see Figure 2). The floor-to-floor height is 3.96 m and the return plenum height is 0.6 m. The raised floor height is 0.4 m. Strip windows are evenly distributed (i.e., a “ribbon” window) in the walls and the window-to-wall ratio (WWR) is 40%. The constructions and the thermal properties of windows change based on each climate and they comply with ASHRAE 90.1 (2004). When doing the design day simulation, ASHRAE 0.4% summer and 99.6% winter design conditions were assumed.

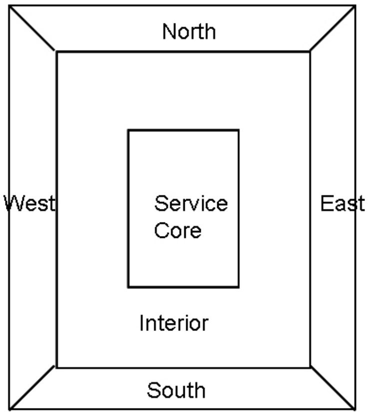

Figure 2. Floor plan of the building model

From 5:00 until 19:00 the system controls the internal air temperature to a cooling and heating temperature setpoint of 23.9°C and 21.1°C, respectively. During the night the system is switched off. Infiltration was assumed equal to 0.333 L/(s m^2) (flow per exterior surface area), constant for 24 hours. The minimum outdoor air flow rate was set to be 0.762 L/(s m^2) (flow per gross floor area).

For zone terminal units of each zone, supply air is distributed through swirl diffusers in interior zones and linear bar grille diffusers in the perimeter zones. Perimeter zones are served by variable speed fan coils (VSFCU) where the fan is on (and heating coil is off) during cooling mode; during heating mode, the fan and the heating coil are on. The building is served by a single variable speed central station air handling unit (AHU) including an air-side economizer, a chilled water cooling coil, a hot water heating coil and a supply fan. The AHU fan is controlled with a static pressure reset strategy. The central plant consists of a central centrifugal chiller with variable speed pumps and a two-speed cooling tower. A gas fired hot water boiler provides hot water to all heating coils. Table 1 shows details of system and plant inputs.

Table 1. Summary of HVAC system configurations

HVAC	
AHU supply air temperature	15.6 °C
AHU fan design static pressure	750 Pa
AHU fan efficiency	75%
AHU part load shutoff[1]	125 Pa
Minimum outside air rate	7.62 E-04 $m^3/s/m^2$
System cycles at night	No
Zone minimum airflow	7.62 E-04 $m^3/s/m^2$
Interior zone reheat	No
FCU design static pressure	125 Pa
FCU design efficiency	15%
Plant	
Chiller design COP	5.0
Boiler design efficiency	80%

LESSONS LEANED

Thermal decay

As described earlier, thermal decay, defined as the temperature rise of the conditioned air in the underfloor plenum, must be taken into account in the UFAD system. In the following, key findings from thermal decay research are summarized .

Figure 3 illustrates the hourly variations of diffuser discharge temperature for each zone in the middle floor during the summer design day period for Cases 1, 2 and 3, which designate series, parallel and ducted plenum configurations respectively (for more detail see Lee et al. (2011)). In the “series” plenum configuration, all conditioned air leaving the air handler first enters the interior plenum and, after gaining heat due to thermal decay, the warmer air leaving the interior plenum then enters each perimeter plenum. In the “parallel” arrangement, the conditioned air from the AHU independently enters each plenum in parallel. The “ducted” option is an idealized configuration in which the conditioned air is ducted all the way to the diffusers and thus, no thermal decay exists in this case. Figure 4 illustrates a daily thermal decay profile (temperature rise) for the middle floor interior and west perimeter zones. By comparing Cases 1 and 3 in Figures 3 and 4, the influence of the thermal decay can be clearly observed. As shown, the series plenum configuration (Case 1) always shows higher discharge temperatures than the air handler supply air temperature (SAT) setpoint due to heat gain in the underfloor plenum. On the other hand, in Case 3 it shows a constant discharge temperature around 15.6°C, which is the same as the air handler SAT. In Case 1 it can be observed that the temperature rise during occupied hours is no lower than 4.6°K for north, 4.8°K for east, 4.6°K for south, 4.2°K for west and 2.6. °K for the interior zone. The temperature rise in Case 1 is always higher in the perimeter zones than in the interior (core) zone. This is due to the “series” plenum configuration where all the conditioned air leaving the air handler first passes through the interior plenum and the warmer air leaving the interior plenum then enters each perimeter plenum. The sharp peaks in the early morning are due to the start-up condition. During the night (the system operation is from hour 06 to 22), the system is off, no conditioned air is supplied into the plenum and thus the heat is accumulated in the plenum. When the system starts to operate in the early morning, the accumulated heat is removed first, producing a high plenum temperature rise in the early start-up period. The slight increase in the discharge temperature at evening time is considered to be due to the decrease in the cooling load at evening, which reduces the supply airflow. The decrease in the airflow can increase the temperature gain of the conditioned air as it travels through the underfloor plenum.

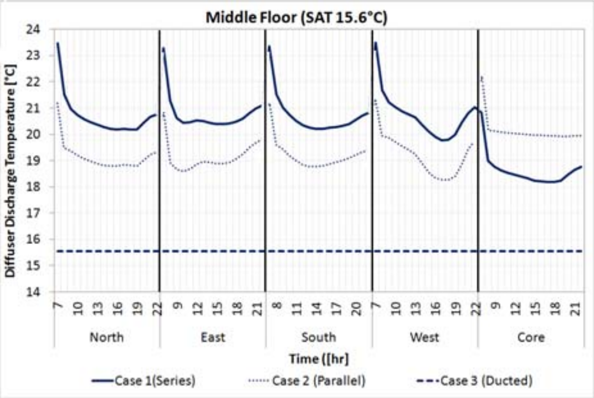

Figure 3. Diffuser discharge temperature

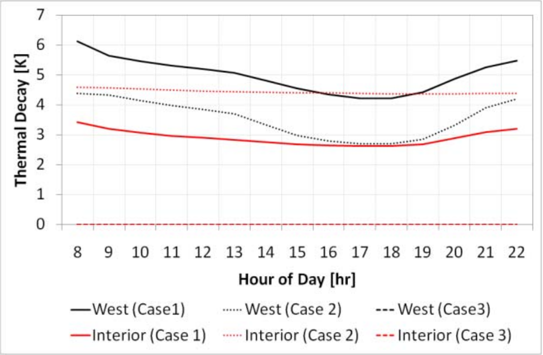

Figure 4. Thermal decay for the west and interior zones (Middle floor)

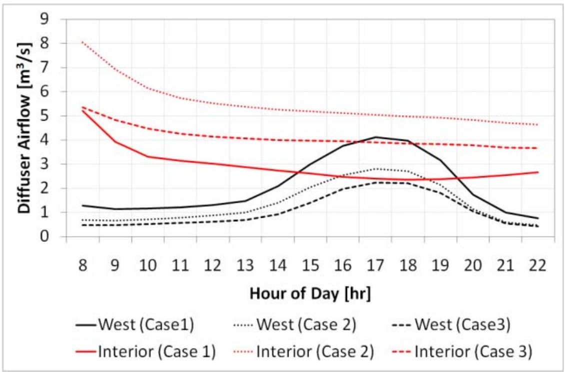

Figure 5. Zone supply airflow rate for the west and interior zones (Middle floor)

Figure 5 presents the hourly supply airflows of the west and interior zone in Cases 1, 2 and 3 during a design day period. In the west perimeter zone, Case 1 (with thermal decay) shows higher airflow rates than Case 3 (without thermal decay) as expected because for Case 1 the larger supply airflow rate results from the increased diffuser discharge temperature. The increase in the airflow in the afternoon is due higher load from solar radiation reaching the west zone.

More importantly, it was also found (not reported here but in Lee et al. (2011)) that plenum configuration and thus thermal decay affect energy consumption. Case 3, without any thermal decay, shows the lowest energy consumption compared to Case 1 and Case 2. The annual total source HVAC energy of Case 3 is 12.7% less compared to baseline Case 1 with the series configuration. From this simple analysis, it appears that reducing the thermal decay may lead to energy savings.

Sizing

During extensive research conducted by the authors it became clear that EnergyPlus autosizing procedures are not always appropriate or not available for UFAD system components (e.g., determining the number of diffusers). In EnergyPlus, sizing UFAD variable speed fan coil units are not straightforward and thus require special care, since it is closely related to the sizing of other system and plant components. In EnergyPlus, the user should explicitly specify the terminal unit (TU) cooling design supply air temperature (SAT). With that information, EnergyPlus sizes each TU based on the peak cooling load determined from the design day calculation. The higher the design SATs are, the larger the TUs become due to the fact that larger amount of air is needed to meet the cooling load for higher TU entering temperatures. In contrast to a conventional OH system, the actual diffuser discharge air temperature in a UFAD system is significantly different from the central air handler SAT due to supply plenum thermal decay, as described above. Thermal decay depends on the amount of air traveling in the plenum. Therefore, TU SAT is a function of the amount of air needed which depends on TU SAT. An iterative process is needed to properly size UFAD system components (Linden et al., 2009). This process was included in several methods developed to more accurately size system components. To determine the correct TU zone design air volume, design day runs are made first, with a high entering temperature assumed for each TU. Then the peak airflow values from the design days are saved for each TU and those values are used for each TU for the annual simulation, after applying a sizing factor specified by the user.

A calculation of the design number of UFAD diffusers was the focus of another method where design day results plus diffuser design volumes determines the number of diffusers used in the annual simulation. This ensures accurate simulation of stratification. In addition to zone component sizing, other HVAC components such as chillers and boilers were also sized based on the design day run results instead of relying on the EnergyPlus autosizing function.

Terminal unit modeling

There are two types of UFAD terminal units (TUs) commonly used in practice, which are not straightforward to model. The first TU is the UFAD VSFCU. The VSFCU is an air system terminal unit consisting of a variable speed fan in series with a heating coil. To simulate this terminal unit, a variable speed fan coil unit model object was developed in EnergyPlus, (see Part V, Bauman et al. (2007)) which can control the cooling air flow rate or reheated supply air to the zone. It has separate maximum cooling and heating airflow rates. Figure 6 shows the control diagram for this unit. In this TU, the air is supplied at low static pressure through an underfloor plenum. The fan is used to control the flow of conditioned air that enters the space. When the fan is off during the deadband condition, the plenum pressure drives the minimum (leakage) air flow rate through the terminal unit. At maximum cooling the fan runs at its maximum speed. At full heating, the fan runs at its heating maximum, which is usually less than the cooling maximum flow rate.

For cooling, control is maintained simply by varying the fan speed. For heating, the unit first tries to meet the heating load by adjusting the discharge air temperature with the airflow fixed at minimum. As the heating load increases and the discharge temperature equals its maximum setting, airflow starts to increase in variable flow mode up to the heating maximum flow rate.

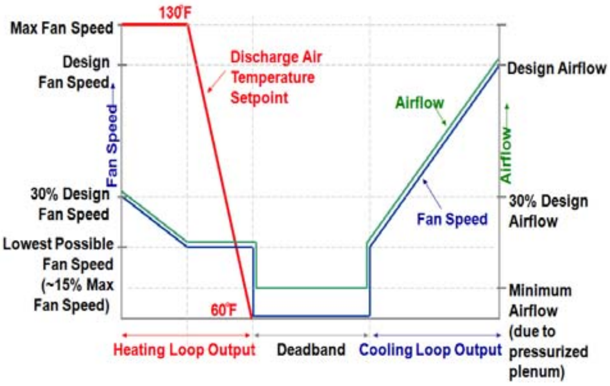

Figure 6. UFAD VSFCU control

Another type of commonly used UFAD TU is similar to the parallel fan powered induction unit. The actual system consists of two components; a VAV diffuser , used for cooling and a constant volume fan coil unit, used only for heating. In order to model this TU, the authors used a work-around. Two TUs are installed in each zone: a unit heater and a regular VAV box without reheat coil. The VAV box supplies primary air to the zone coming from the central AHU for ventilation purposes. Heating is provided by the unit heater, which uses recirculated (secondary) air induced from the space to warm the space. By operating those two terminal units at the same time, UFAD fan powered induction unit can be modelled reasonably.

Room air stratification

Room air stratification (RAS) is a key characteristic of UFAD systems. Increased stratification is associated with improved energy efficiency and is considered a key marker of well performing systems. However, there are many important factors that must be considered when modeling stratification including its dynamic nature and its interrelationship with supply plenum performance during operation. Stratification level is affected by the following factors:

- Diffuser characteristics (shape, angle and effective area)
- Number of diffusers
- Number of thermal plumes
- Airflow rate (this is a function of SAT and load)
- Cooling load

Among those factors, the impact of the number of diffusers on the stratification level is illustrated in Figure 7 (Bauman et al. In press). . It should be noted that these results came from swirl type diffusers, not other diffuser types. The stratification level is represented by the temperature difference in the “occupied zone” the region between foot and head level of a standing person. Figure 7 shows the stratification level in the middle floor west perimeter zone during a summer day in San Francisco with AHU SAT of 17.2 °C, using linear bar grille diffusers.

In the baseline case, the stratification remains high in the morning and in the early afternoon due to the low supply airflow at low cooling load condition in the west zone. However, in the late afternoon stratification is reduced due to increased supply airflow caused by the increase in cooling load (causeddue to solar radiation entering the west zone in the late afternoon).

On the other hand, if the number of diffusers is doubled compared to the baseline case, the stratification remains high throughout the whole day regardless of the cooling load conditiong. More importantly, 13% of the HVAC energy saving can be achieved just by increasing the number of diffusers by a factor of two, indicating that generating more stratification by increasing the number of existing types of diffusers or providing better diffuser for the stratification can lead to the energy saving.

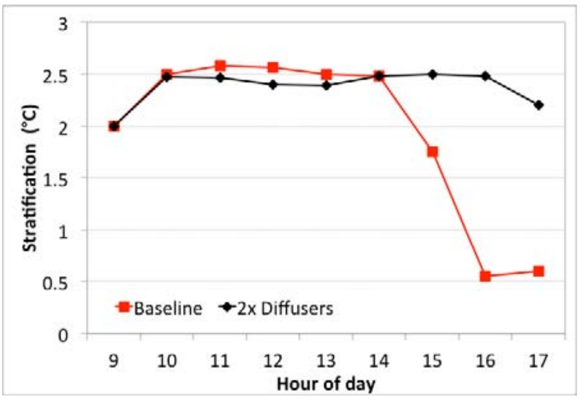

Figure 7. Stratification with the number of diffusers

The following table summarizes the impact of the air handler supply air temperature (AHU SAT) on the stratification level (Bauman, et al. In Press). It shows the results of stratification in the middle floor interior zone obtained from the UFAD cooling load design tool (Schiavon et al., 2010), developed by the authors. The only difference between Cases 1 and 2 is that the AHU SAT of Case 2 is reduced from 17.2°C to 13.9°C. As shown in Table 2, lowering the SAT results in increased stratification from 1.3°C to 2.4°C relative to the baseline case. This results from decreased zone supply airflow caused by the reduced SAT. Case 2 zone airflow is decreased by 25% compared to Case 1.

Table 2. Influence of air entering the supply plenum on room air temperature stratification

	Case 1	Case 2
Temperature of Air Entering Supply Plenum (AHU SAT)	17.2 °C	13.9 °C
Stratification	1.3 °C	2.4 °C

Thermal comfort

Typically, interior zones have no terminal heating equipment in UFAD systems. It is common practice in California to not use a central heating coil in the AHU in UFAD systems. The purpose of the heating coil would be to maintain thermal comfort in interior zones. Some ramifications of this choice are discussed below.

The authors used zone operative temperatures (average of zone dry bulb and mean radiant temperature) to assess occupant comfort during occupied hours. For UFAD, the temperature in the lower occupied region of the zone is used for the dry bulb component. Operative temperature provides an indicator of whether or not comfort problems would occur, especially for interior zones when operating near heating conditions.

Figures 8 and 9 (Webster et al., 2010) show operative temperature histograms for three studied SATs (13.9, 15.6 and 17.2°C) under Sacramento and San Francisco climates. The curves show cumulative results on the right hand axis. If it is assumed that heating is needed when the operative temperatures is below 21°C (equal to the heating dry bulb set point), lower SATs, i.e. SAT of 13.9°C compared to 15.6°C and 17.2 °C, appear to affect comfort very little in San Francisco. However, in Sacramento they have more of an effect; 24% below 21°C for SAT =13.9°C, and 13% for SAT= 15.6°C. Other work by the authors indicates that these coils may have have a significant energy impact. In San Francisco, it appears that there is little risk of overcooling interior zone occupants, which confirms common practice in the area. However, yet to be published results indicate that in Minneapolis a central AHU heating coil is essential to maintain comfort in interior zones, with significant consequences on heating energy use. With this knowledge, designers can make a judgment about whether to install a central heating coil in the AHU to mitigate low interior zone temperatures or possibly rely on occupants controlling their diffuser to manage their comfort instead. A related issue is minimum ventilation settings. When cooler SATs are used, if the interior zone minimum ventilation rate is to be maintained (as opposed to letting it go to zero, for example), comfort problems could be exacerbated.

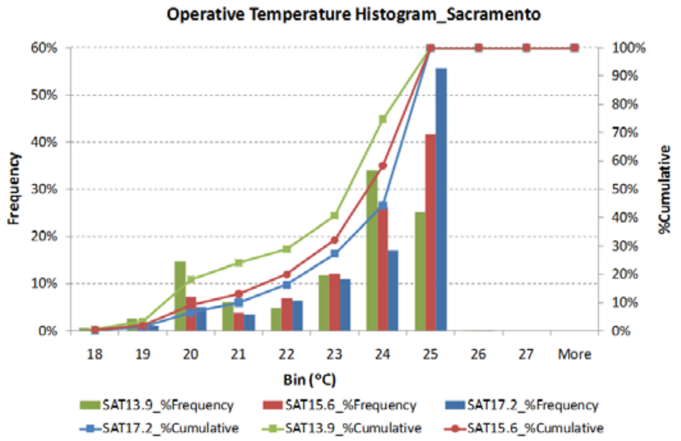

Figure 8. Comfort histogram (Sacramento)

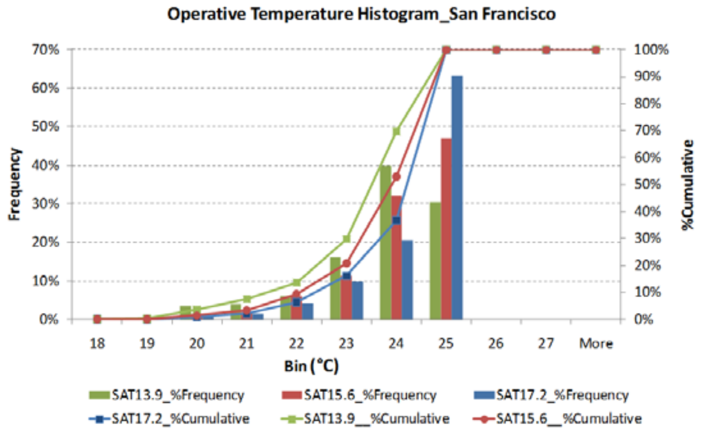

Figure 9. Comfort histogram (San Francisco)

CONCLUSION

The authors have used EnergyPlus/UFAD extensively and participated in the design and implementation of refinements to the EnergyPlus/UFAD module. Through this experience many lessons have been learned on how to properly simulate these systems. In this paper, the following topics that need careful consideration during the modeling process of UFAD systems are summarized.

1) Thermal decay – Thermal decay has a significant impact on the overall UFAD performance and thus it needs to be accurately modeled.

2) Sizing and fine-tuning of UFAD system components – Since UFAD systems have several unique features compared to conventional systems such as thermal decay and room air stratification, properly sizing UFAD systems is not straightforward and needs special care.

3) Modeling terminal unit types commonly used in UFAD – A new model has been implemented in EnergyPlus to properly model VSFCUs. In addition, a work-around was introduced in the paper to show how to model another commonly used UFAD terminal unit, which is similar to parallel fan powered induction unit.

4) Stratification - Special care should be taken to properly model stratification in UFAD systems, since it has significant impact on UFAD performance.

5) Implications of system design and operation on thermal comfort – Results shown in this paper indicate that system operation has an impact on thermal comfort, especially in interior zones (since they are not directly heated). In moderate climates like California, a central AHU coil may not be needed but in colder climates like Minneapolis, interior zone comfort can be adversely affected without central heating coils.

These lessons are all important for design practitioners and researchers when attempting to simulate UFAD systems and to avoid pitfalls and improper assumptions that can lead to inaccurate results.

ACKNOWLEDGEMENT

For valuable advice, suggestions and revision, the authors would like to thank Allan Daly of Taylor Engineering, Alameda, CA, US. The present work was supported by the Center for the Built Environment, University of California, Berkeley and the California Energy Commission - PIER project 500-08-044.

REFERENCES

Alajmia, A. and El-Amer, W., 2010. “Saving Energy by using Underfloor-air-distribution (UFAD) System in Commercial Buildings.” Energy Conversion and Management, Vol. 51, Issue 8, pp. 1637-1642, August.

ASHRAE, ASHRAE Standard 90.1-2004, Energy standard for buildings except low rise residential buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2004.

Bauman, F., 2003. “Underfloor Air Distribution (UFAD) Design Guide. Atlanta: ASHRAE.” American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Bauman, F., Schiavon, S., Webster, T. and Lee, K. H., 2010. “Cooling load design tool for UFAD.” ASHRAE Journal, Vol. 52 Issue 9, pp. 62 ~ 71. http://escholarship.org/uc/item/7hh1t2z4

Bauman, F., Schiavon, S., Webster, T. and Lee, K. Hoyt, T., Feng, Q., Dickerhoff, D. In press. “Advanced Design and Commissioning Tools for Energy Efficient Building Technologies. ”Final Project Report submitted to CEC PIER Program. CEC Contract 500-06-049. Center for the Built Environment, University of California, Berkeley, CA.

Bauman, F., Webster, T. Jin, H., Lukaschek, W., Benedek, C., Arens, E., Linden, P., Liu, A., Buhl, F., and Dickerhoff, D. 2007. "Energy Performance of Underfloor Air Distribution Systems." Final Project Report submitted to California Energy Commission (CEC) Public Interest Energy Research (PIER) Program, CEC-500-2007-050. Center for the Built Environment, University of California, Berkeley, CA, April. http://www.energy.ca.gov/2007publications/CEC-500-2007-050/

DOE. 2010. “Input-output Reference.” EnergyPlus Manual version 6.0, U.S. Departement of Energy, October

Lee, K. H., Schiavon, S, Bauman, F, and Webster, T. In press. “Thermal decay in underfloor air distribution (UFAD) systems: Fundamentals and influence on system performance” Submitted to Applied Energy.

Linden, P., Yu, J. G., Webster, T., Bauman, F., Lee, K. H., Schiavon, S. and Daly, A. 2009. “Simulation of Energy Performance of Underfloor Air Distribution (UFAD) Systems” – Final Report to CEC BERG Program. CEC Contract No. 54917A/06-05B. Center for the Built Environment, University of California, Berkeley, CA.

Liu, Q. and P. Linden, 2008. “The EnergyPlus UFAD Module.” Proceedings of SimBuild 2008 (In Press), Berkeley, CA, July 30-August 1.

Schiavon S, Lee KH, Bauman F, and Webster T. 2011. Simplified calculation method for design cooling loads in underfloor air distribution (UFAD) systems. Energy and Buildings, 43 (2-3) , 517-528. doi:10.1016/j.enbuild.2010.10.017 www.escholarship.org/uc/item/5w53c7kr

Webster, T., Bauman, B., Buhl, F. and Daly, A., 2008. “Modeling of Underfloor Air Distribution Systems.” Proceedings of SimBuild 2008, Berkeley, CA, July 30-August 1.

Webster, T., Lee, K. H., Bauman, B., Schiavon, S., Hoyt, T., Feng, J. and Daly, A., 2010. “Influence of supply air temperature on underfloor air distribution (UFAD) system energy performance.” Proceedings of SimBuild 2010, New York, NY, August 11-13.

Bauman, F., Jin H., and Webster, T., 2006. “Heat transfer pathways in underfloor air distribution (UFAD) systems.” ASHRAE Transactions, 112(2).

Woods, J. E., and Novosel, D., 2008. “Comparative Analysis of Conventional and Underfloor Air Distribution System Performance using the Air Diffusion Performance Index Method.” Extended Abstract of Technical Report, The National Center for Energy Management and Building Technologies