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MODELING OF UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEMS

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ABSTRACT

In this paper, we discuss the development of a module that is capable for the first time of simulating UFAD systems in EnergyPlus. We describe the new models for EnergyPlus that simulate two important elements of these systems: underfloor air supply plenums and room air stratification under cooling operation. These algorithms were developed over a 5-year period of intensive interdisciplinary work consisting of theory, bench-scale and full-scale experimental testing, and computational fluid dynamics (CFD), analytical, and empirical modeling. We describe the modeling methods, show examples of a preliminary validation based on experimental data, and present results of research studies that have significantly contributed to a more complete understanding of the behavior of UFAD systems.

INTRODUCTION

Underfloor air distribution is an innovative technology that uses the underfloor plenum below a raised floor system to deliver space conditioning in offices and other commercial buildings. The use of UFAD has increased in North America during the past decade because of the broad range of potential benefits that it offers over conventional overhead air distribution systems. (Bauman and Webster 2001; Bauman 2003). Energy simulation tools are a critical missing link in the development of UFAD technology and are the only practical means of rigorously evaluating performance of these complex systems. Moreover, recent unpublished research by the authors indicates simulations that do not explicitly include supply plenums and detailed surface heat balances will not accurately capture important effects.

The technical approach for the project featured a coordinated effort by the research team to conduct extensive experimental and modeling studies to form a solid foundation for the development and validation of the two new simplified models for implementation into EnergyPlus, one on room air stratification (RAS) and one on underfloor plenums. This coordinated, multi-disciplinary approach has proven to be very successful in developing the required EnergyPlus modules as well as generating much needed new knowledge and improved understanding of the fundamental principles of UFAD system design, operation, and energy performance.

METHODS

Compared to overhead well-mixed systems, there are two primary characteristics of UFAD systems that must be accounted for to accurately simulate the energy performance of UFAD systems: (1) room air stratification, and (2) underfloor plenum thermal performance. We describe below the combination of theoretical and experimental methods we used to develop UFAD modules for these features in EnergyPlus as well as important additions to HVAC systems.

Room air stratification full scale testing

Analytical modeling techniques along with idealized bench scale tests were used to establish a physical basis for modeling room air stratification. This work is described in a companion paper by Liu and Linden (2008). This work resulted in establishing a two-layer approach to modeling the stratification in a room.

To provide a detailed understanding of how room air stratification is influenced by various design and operating conditions and to verify the findings of the theoretical work, we conducted full-scale experiments in a test chamber configured to simulate an office space.

The test facility consisted of a test chamber configured like an open office space and an adjoining weather chamber that allowed us to simulate solar gain and window heat transfer. Independently controlled HVAC equipment served these two spaces. The test room was a 7.9 m (26 ft) square with an area of 63 m² (676 ft²) and a height of 2.7 m (9 ft).

Figure 1 shows the layout of the test chamber. Besides instrumentation, the room contained thermal manikins, personal computers, desk lamps and other equipment to create a typical office environment. The weather chamber was separated from the test chamber by a curtain wall with a double glazed clear glass window. An array of quartz lamps provided simulated solar radiation equivalent to west low-e facing glass at peak summer conditions in Kansas City.

The test facility was supported by a 150-channel data acquisition system that measured air and surface temperatures, as well as airflow and underfloor pressure. These measurements provided sufficient detail to allow us to calculate a detailed heat balance of the chamber. A complete description of full-scale testing can be found in (Bauman et al. 2007).

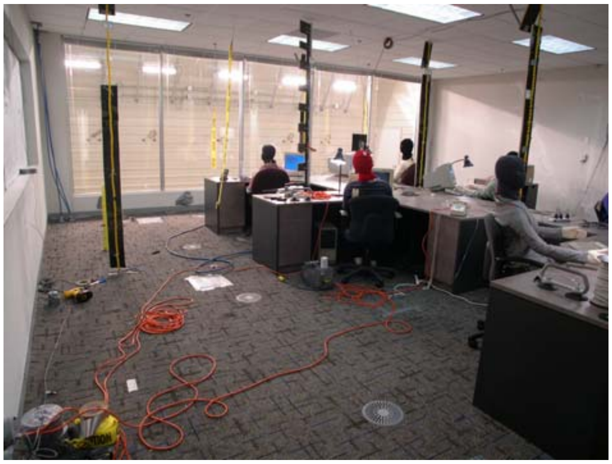

Figure 1: Photo of test chamber

In Table 1 we list the internal loads for each workstation, as well as their assumed convective fractions.

Table 1: Workstation internal loads breakdown

Internal gains breakdown	W, ea.	% Conv.
Printer	130	90%
CPU Power	33	90%
CRT Monitor power	65	65%
Manikin power	75	40%
Task light	60	40%
Total WS power	255	57%

Interior zones. We investigated the performance of three diffuser types that we typically expect to find in practice in interior zones: (1) standard swirls (SW), passive (i.e., not modulated) but user adjustable; (2) modulated variable area (VA); and (3) passive swirls with horizontal discharge (HD) that mimic to some degree displacement ventilation airflow patterns. Figure 2 (see figures at end of paper) shows test results (normalized to the same control point and supply air temperature) that compare the stratification performance for these diffusers at typical design conditions. As shown, the standard swirl diffusers operate similar to variable area diffusers but both are distinctly different from horizontal discharge swirl diffusers. Furthermore, standard swirl performance varies depending on operating conditions (Bauman et al. 2007), whereas VA and HD diffusers exhibit little variation. We note, however, that our experience with actual systems indicates that in practice real systems operate over a smaller range of variation than we tested in the laboratory.

Perimeter zones. Chamber test results for perimeter zones under peak solar load conditions exhibit performance similar to that of interior zones in the occupied zone (lower sub-zone) but more stratified in the upper sub-zone. We tested linear bar grilles, a common air distribution method used in practice, for two cases with different diffuser configurations, and for a case with the venetian blinds closed. The overall room air stratification (floor to ceiling temperature difference) for the latter is significantly greater than the others due to the effects of a stronger window plume (see Bauman et al. 2007 for more detail).

Room air stratification empirical models

In addition to modeling the supply and return plenums as fully mixed zones, we assume that the room is divided into two fully mixed sub-zones, as shown in Figure 3. 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.

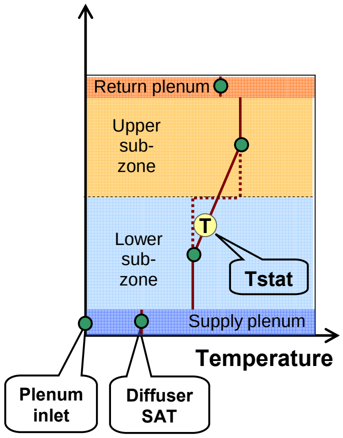

Figure 3: EnergyPlus multi-layer UFAD model

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 the EnergyPlus models. However, we found that the ideal analytical formulations developed by Liu and Linden (2008) were limited in their ability to represent the results of the full-scale testing. We also found that the numerical models based on these formulations could not be easily incorporated into the EnergyPlus structure. The former limitation we attributed to “real world” differences in the effects of radiant exchange, coalescing of multiple plumes and plumes at different heights, imperfect mixing in the lower sub-zone, the impact of different diffuser types, and our inability to accurately identify the stratification height in full-scale experiments.

Comparisons between full-scale and bench-scale experiments, however, indicated that the theoretically derived dimensionless parameter, Gamma, when plotted against Temperature-effectiveness ((T_eff) a non-dimensional representation of the room air stratification; see nomenclature) captured the essential physics of the stratification process. Therefore, we used correlations of Gamma versus T_eff using the full-scale test data shown in Figure 4 (see figures at end of paper) for our interior zone model in EnergyPlus.

Supply air plenum testing and modeling

We used a combination of full-scale testing and computational fluid dynamics (CFD) modeling to develop a simplified model suitable for implementation in EnergyPlus that was capable of calculating the thermal performance of underfloor air supply plenums. Steady state testing was conducted in a full-scale plenum test facility (22 ft x 48 ft x 1 ft) (Jin et al. 2006). We conducted tests for two different inlet conditions, (1) single focused jet, and (2) inlet vanes/two jets, to provide validation quality data for the plenum CFD model.

A model using the ANSYS CFX CFD program was developed to match the geometry of the plenum test facility. The CFD plenum model incorporated a standard k-ε turbulence model and a source term to represent the resistance of the pedestals that are spaced uniformly throughout the plenum. The model was validated by comparison with the full-scale experimental data. The computed air temperatures, velocities and surface heat fluxes generally agreed well with the measured data. More importantly, the discrepancies between computed and measured total heat gain of the plenum were less than 10%.

We used the validated CFD plenum model to conduct a larger number of “numerical experiments” to investigate the energy performance of underfloor plenums over a wide range of realistic plenum airflow configurations and operating conditions. A CFD sensitivity study demonstrated that total airflow rate through the plenum was the primary factor in determining the surface convection coefficients on the top of the slab and the underside of the raised floor panels. Since we can easily specify convection coefficients within EnergyPlus, we decided to use a simplified approach where we assumed the plenum to be a well-mixed zone with the expected average convection coefficient values for these two surfaces described as a function of total airflow rate (Bauman et al. 2007). As indicated above, we expect this assumption to result in errors of less than 10% in the prediction in the underfloor energy balance.

EnergyPlus integration

Non-uniform zone models: EnergyPlus is based upon the heat balance method within a single zone. The basic zone model convectively couples all the surfaces to a single room air node. Further development of the program has led to the introduction of multiple air node zone models. The available models are divided into two primary types: models with user-specified predefined nodes, and the models that divide the zone vertically into a series of well-mixed sub-zones with thicknesses depending on load and airflow rate. In order to choose a non-uniform zone model, a RoomAirModel object was created. This object allows the user to choose from among a variety of non-uniform models from well mixed to various multi-node models including two-node models for interior and perimeter zones of UFAD systems (DOE 2007). Each choice requires further input specific to the model chosen. For the UFAD project, we developed two new room air models: interior UFAD and exterior UFAD. Both are two node (two sub-zones) models similar to the EnergyPlus’ displacement ventilation model. For modeling these zones, we developed an entirely new module, *UFADManager*. This module contains the routines that set the access points, initialize parameters, sets input defaults for zone model and diffuser type, sets convection coefficients for room surfaces, and calculates sub-zone boundary height.

The most important feature of the UFAD zone models is that separate convective heat balances are performed yielding separate average air temperatures for each sub-zone. The convective heat transfer at zone surfaces is calculated at the subzone level using the subzone air temperatures. We found that the most straightforward way to simulate stratification is to divide the convective energy gains between the upper and lower sub-zones. We used the Gamma vs. T_eff correlations shown in Figure 4 to split the previous time step's extraction rate (i.e., the net convective gains) between the sub-zones.

Supply air plenums: A major barrier to modeling UFAD systems has been the inability to model supply air plenums. In the early phases of the UFAD project, we enhanced EnergyPlus to permit a general configuration of supply plenums in the supply air path. This gives the program the capability of using various series and parallel supply plenum configurations. We still model these plenum zones as well-mixed zones with a single average air temperature. We can model temperature gain (thermal decay) by concatenating plenums in series. We thought that treating supply plenums as normal zones would prove to be inadequate. However, validation studies as described above showed that simply varying the convection coefficients at the upper and lower surfaces produced good agreement.

New HVAC systems

At the beginning of the UFAD project, we identified two HVAC modeling capabilities not yet in EnergyPlus that are vital to providing a comprehensive simulation of UFAD systems: a variable-speed fan terminal unit and return air bypass (RAB) capability.

Variable-speed fan coil: To simulate systems commonly used in practice, we developed a variable speed fan coil unit, which can control the flow of cool or reheated supply air to the zone. It has separate maximum cooling and heating airflow rates. The model is fully iterative – it makes no assumptions about the linearity of its subcomponent models. An example of the model's use is contained in example input *5ZoneSupRetPlenVSATU.idf* contained on all EnergyPlus releases since version 1.2.1.

Return air bypass (RAB): EnergyPlus has a theoretically general HVAC duct configuration capability, but the allowed configurations have always been limited in practice. With this capability, single splitters on the air-system supply side could be used to simulate single and dual duct systems. There was no provision for a mixer and splitter, as is needed for a return air bypass system, or any means for controlling such a system. This capability is needed to accurately simulate UFAD systems since these systems often use a higher than normal supply air temperature. A conventional single duct setup would have difficulty removing sufficient moisture from the mixed air to maintain comfortable zone humidity levels without using reheat. RAB configurations are often applied in humid climates to mitigate this problem in UFAD systems.

Creating the capability to model return air bypass duct configurations in EnergyPlus required three new elements: A primary air loop mixer, an air-side branching pass-through unit (called Duct that operates similar to the Pipe component in the Plant program), and a flow controller for the branch which consists of a new setpoint manager. Figure 5 shows a schematic of the RAB system.

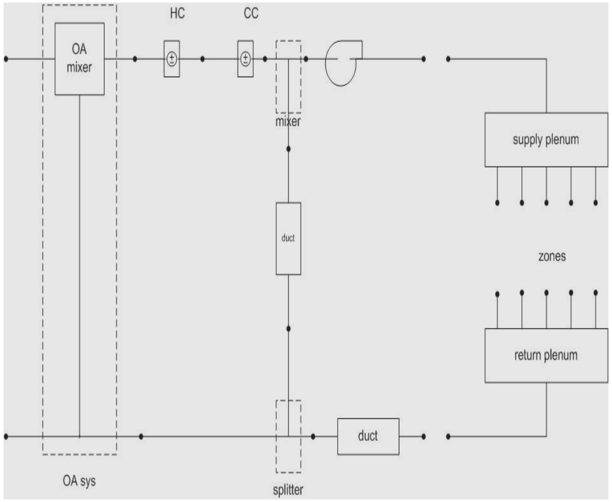

Figure 5: Return air bypass schematic diagram

The complete RAB simulation capability was released with EnergyPlus version 1.2.3 in October 2005. An example input illustrating the capability is contained in *5ZoneSupRetPlenRAB.idf*.

Test chamber model and simulation interface

To assist with validating the EnergyPlus/UFAD simulation module we developed a fully detailed EnergyPlus model of the test chamber as shown in Figure 6. We divided walls and floors into multiple segments to allow direct assignment of solar gains to each segment to assist with validation of the perimeter UFAD simulation model. Because the quartz array does not represent true solar gain or its spectral distribution, we used a special version of EnergyPlus for perimeter zone simulations that included a customized method of accounting for the solar gain (Winkelmann 2006). Workstation furniture was modeled by replacing five of the fifteen floor segments with an insulated surface.

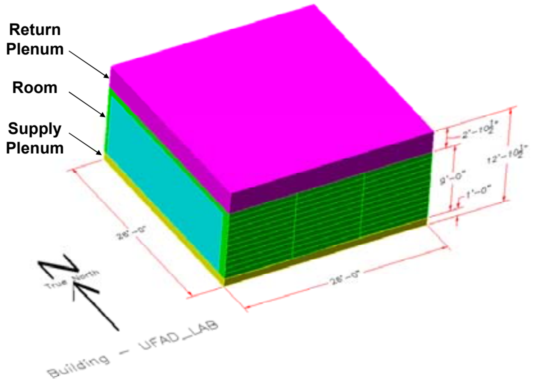

Figure 6: Test chamber model

We developed a spreadsheet-based interface (Daly 2006) to manage EnergyPlus input and output and to facilitate reconfiguration of the test chamber model to support a variety of sensitivity studies. Figure 7 is an information flow diagram of this interface.

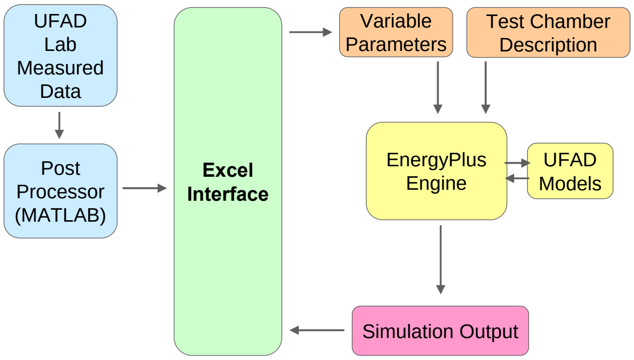

Figure 7: Test chamber simulation interface and information flow

We used test chamber measured outside wall surface temperatures to establish thermal boundary conditions; these were modeled using EnergyPlus "otherside coefficients." Internal loads and HVAC system performance data were input into the EnergyPlus simulations using processed data from the laboratory data acquisition system.

We developed methods to display the simulation results against measured test chamber data. These included tables and charts to track the chamber energy balance and to compare simulation results to measured data. Figure 8 shows an example of the chart we used to display comparison data.

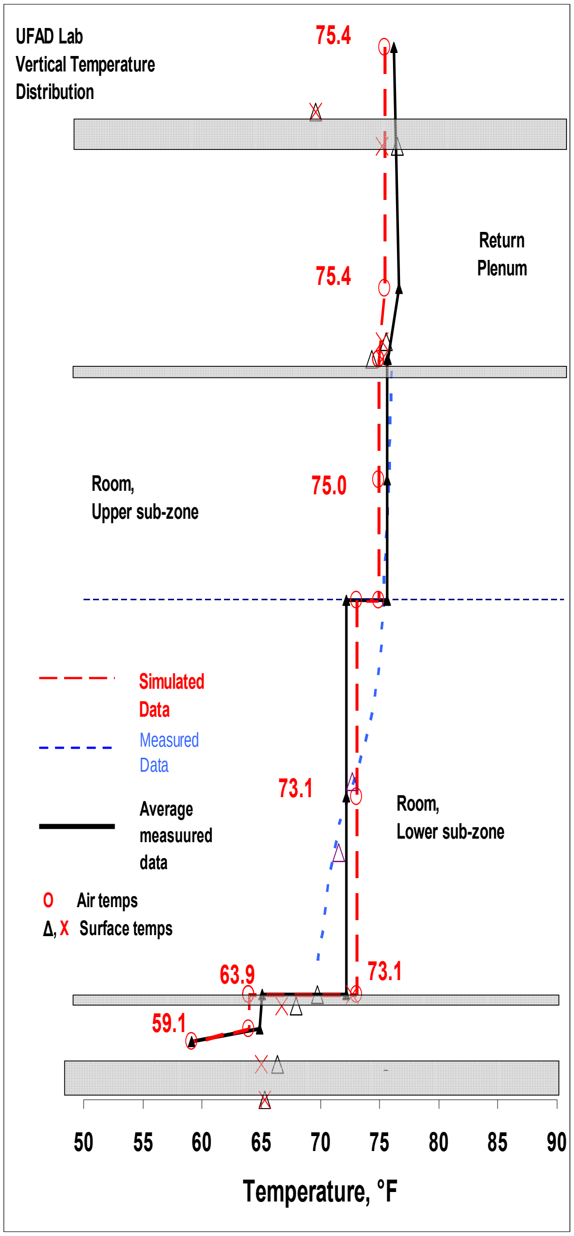

Figure 8: Temperature profile showing measured vs. simulated air and surface temperatures

RESULTS AND DISCUSSION

Heat transfer studies

One important outcome from the EnergyPlus simulations using the test chamber model was our ability to model the details of the heat transfer mechanisms that take place in these systems. Earlier work on this topic used a simplified modeling approach (Bauman et al. 2006). To accomplish this we reconfigured the chamber model to simulate an interior zone of the middle floor of a multi-story

UFAD building and conducted steady state simulations. For convenience, we defined the supply plenum bottom to be connected to the return plenum top so the two surface temperatures are equal. (A dynamic simulation would not be configured this way; it would include floor-to-floor heat transfer including thermal mass effects.) Then we set all the walls to be adiabatic and created an output report that contained all the conduction and convection components at each surface; we then back calculated the radiative component from these two. We summarize the results for one example in Figure 9 (below). Note that this figure shows the overall convective gain/loss fractions (of total internal load) in the two plenums and room that result from the complex heat transfer processes illustrated on the right side of the diagram. We can draw several important conclusions from these results:

- A substantial portion of the room load ends up in the supply plenum (48%). This is driven by heat gain from above through the raised floor and below from conduction through the slab.
- Radiation (i.e., *net* radiation at the surface) exchange between floor and ceiling is augmented by radiation from the internal equipment and people loads so that there is a net positive radiant heat transfer onto both the ceiling and floor (as opposed to just exchange between floor and ceiling)
- There is a net heat loss from the return plenum (-9%) so that the return air is being cooled as it passes to the air handler (AHU).
- The room load (extraction rate) is reduced (61%) compared to CAD systems by the loss to the supply and return plenums thereby reducing airflow requirements.

Validation results

As a preliminary step in our validation process (a full uncertainty analysis has not yet been completed) to test the efficacy of the empirical models for interior zones we ran the chamber model for 27 tests covering three diffuser types; VA, SW, and HD. The results in Figure 10 show the root mean square error (RMSE) for the differences between measured and simulated temperatures for selected air and surface temperatures. Except for the raised floor top temperature, the RMSEs for most temperatures are below 1°C, which indicates good predictability for the room stratification and plenum models. We expected the measured raised floor top temperature to be slightly lower than simulated because the temperature near the floor for the simulated case is equal to the average temperature of the lower sub-zone, while for real systems it is a few degrees cooler due to stratification in the lower sub-zone.

CONCLUSION

The small overall errors between experimentally measured and simulated air and surface temperatures shown in Figure 10 indicate that the room air stratification and supply plenum models developed under this project are capable of simulating room air stratification and supply plenum heat transfer relatively accurately. This indicates that we will be able to simulate the energy performance of interior zones (and associated supply plenums) of UFAD systems with confidence using EnergyPlus/UFAD. Furthermore, we have demonstrated that the theoretically derived parameter Gamma represents the underlying physics of the stratification process well. These, along with the development of HVAC component models, represent major steps toward providing a complete and fully validated EnergyPlus simulation module for UFAD systems. Ongoing work will complete the development of a validated perimeter zone model later in 2008. This new version of EnergyPlus will be instrumental in a wide variety of studies to investigate the energy performance of these systems while providing practitioners the ability to simulate these systems more accurately than is currently possible.

ACKNOWLEDGMENT

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NOMENCLATURE

$$\text{Gamma} = \quad \Gamma = \frac{(Q \cdot \cos\varphi)^{\frac{3}{2}}}{m \cdot \left(\frac{n}{m} \cdot A_{eff}\right)^{\frac{5}{4}} \cdot (0.0281 \cdot W)^{\frac{1}{2}}}$$

Gamma represents the ratio of diffuser momentum to thermal plume buoyancy which embody the driving forces for creating stratification. (See Liu and Linden 2008 and Bauman et al. 2007.)

Q = room airflow

A_{eff} = Diffuser effective area; Cos θ = discharge angle for diffuser flow

n = number of diffusers; m = number of plumes

W = total zone plume convective energy; for simulations we use the room extraction rate (i.e., the net convective energy in the zone)

Temperature_effectivness, T_eff $= (T_{OZ} – T_S)/(T_r - T_S)$; this repesents the ratio of the lower sub-zone to total room convective energy, where T_{OZ} = average lower layer (occupied zone) temperature; T_S = supply air temperature to the room; and Tr = return temperature at the top of the room

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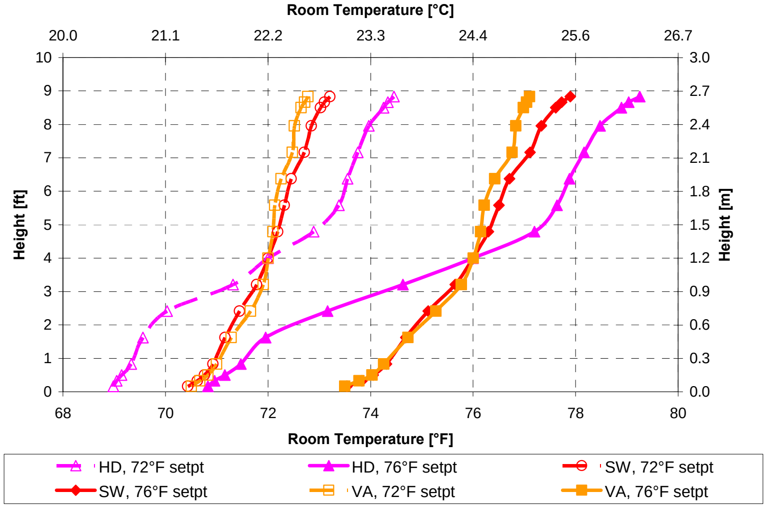

Figure 2: Comparison of VA, SW and HD diffusers under peak design conditions for interior zones

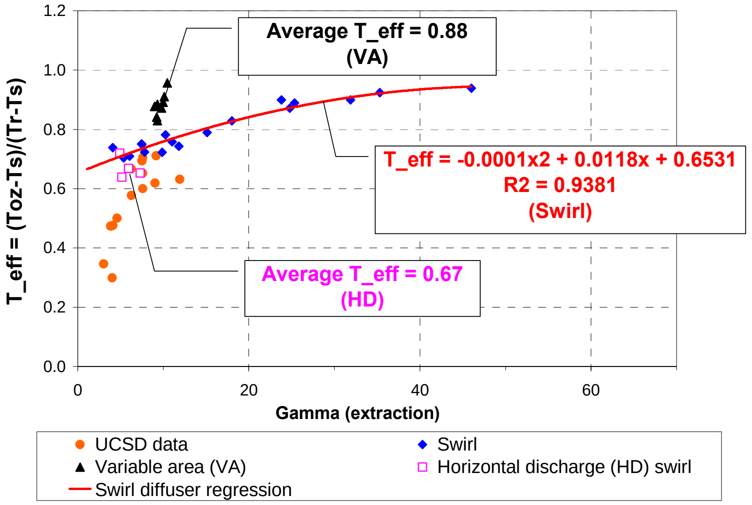

Figure 4: Empirical correlations, Gamma vs.Temperature_effectivness (T_eff) for interior zones and various diffusers

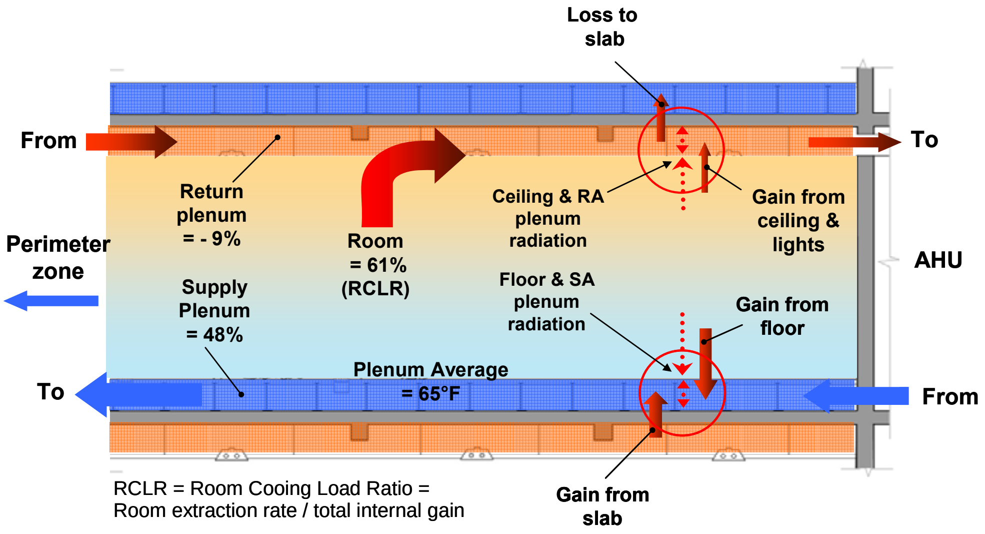

Figure 9: Heat transfer analysis summary showing the distribution of convective gains as fractions of total heat gain to the room/plenums system

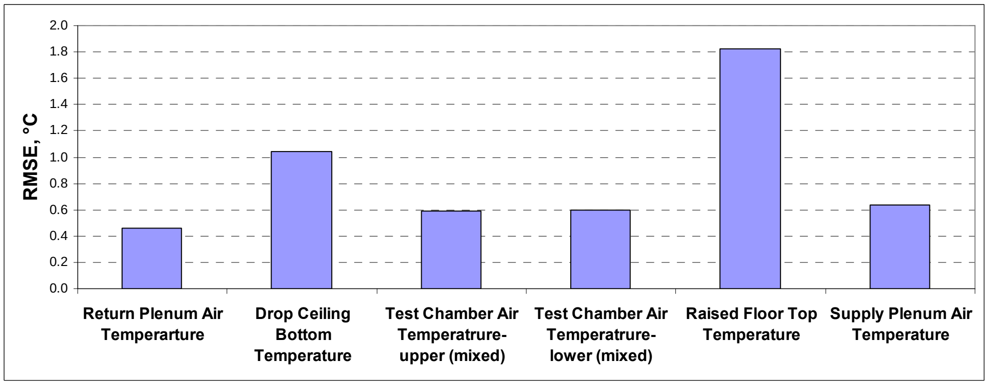

Figure 10: Validation results for all tests; temperature RMSE for selected location