Cooling via Underfloor Air Distribution: Current Design Issues and Analysis Options

Marlin S. Addison
Clinical Assistant Professor
Arizona State University
Tempe, Arizona
Marlin.Addison@doe2.com

Daniel H. Nall, P.E., AIA
Senior Vice President
Flack + Kurtz Engineers
New York, New York
Daniel.Nall@ny.fk.com

BACKGROUND

Over the past two decades, displacement ventilation systems have received significant attention and use in Scandinavia, Europe and Japan. Displacement ventilation differs from conventional "mixing" or "dilution" ventilation by relying less on mixing via kinetic forces and more on stratification via buoyancy forces. With the tremendous increase in workplace automation in recent years, raised floor systems have found wider application due to their facility management advantages (e.g., flexible space and cable management). Accordingly, this has increased interest in the use of underfloor air distribution systems, which are naturally well-suited as displacement ventilation applications. The behavior of displacement ventilation systems, however, depends on heat and mass transport mechanisms that are computationally more complex than those required to analyze conventional mixing ventilation systems. These requirements are less forgiving to common simplifications contained in widely used HVAC design and energy analysis tools. Despite the potentially significant advantages of underfloor air distribution, the shortcomings in existing design and analysis tools will impede the use of underfloor air distribution systems.

In this paper we briefly describe the significant features, potential advantages, and design issues associated with underfloor air distribution. We then briefly describe the simplifications of the current and emerging whole building energy analysis and HVAC design simulation tools that limit their utility for the analysis of underfloor systems. We conclude by recommending an interim energy modeling approach and longer term developments that will better support the design and energy analysis of underfloor air distribution systems.

UNDERFLOOR AIR DISTRIBUTION SYSTEM DESCRIPTION

An underfloor air distribution system is broadly similar in concept and control to conventional single-duct VAV systems with the following general differences: 1) the distribution of conditioned air is accomplished below a raised floor system with supply registers located in the floor or in personal work stations, fed from an underfloor supply plenum; 2) since air is supplied in much closer proximity to occupants than in conventional overhead systems, supply air temperatures must be higher, e.g., 60ºF to 65ºF; 3) the velocity of delivered air is selected to be too low to support thorough mixing within the space served — the result is a vertical displacement-style ventilation regime; and 4) varying degrees of individual occupant thermal and ventilation control provided via individually operable supply registers.

A recent survey of practices in underfloor air distribution (Bauman and Webster, 2001) identified three basic approaches: 1) supply air delivered via passive floor registers and/or fan-powered terminal boxes supplied by a pressurized underfloor plenum and central air handler; 2) supply air delivered via active, locally-controlled, fan-powered registers (in the floor or workstations), supplied by a very low-pressure underfloor plenum and central air handler, and 3) supply air delivered via underfloor ducts to terminal devices or supply outlets.

The lower supply velocities typical of underfloor air distribution systems result in each thermal zone being subdivided vertically into a lower, occupied region (e.g., floor level to 5 ft.) and an upper, unoccupied region (e.g., from 5 ft. above floor height to ceiling height). Supply velocities are sufficient to support mixing only in the lower, occupied region, leaving the upper, unoccupied region to function as a stratified displacement region.

From: *Cooling Frontiers: The Advanced Edge of Cooling Research and Applications in the Built Environment*. 2001. College of Architecture and Environmental Design, Arizona State University

Heat gains within the space do not necessarily participate in loading the lower, occupied air mass. Convective loads originating within the upper displacement region don't mix with the lower occupied air mass, and some fraction of the loads originating in the lower occupied air mass are transported into the upper displacement region via convective plumes without thoroughly mixing with the occupied air mass. As a result, the total sensible load on the occupied air mass is reduced which permits a reduction in the total design supply volume.

Airborne contaminants originating within the space, as well as outside ventilation air, follow similar mixing and displacement regimens. The result is improved ventilation efficiency and reduced contaminant concentrations in the occupied air mass (Faulkner, et. al., 1995; Yuan, et. al., 1999). A more complete description of underfloor air distribution systems, including a detailed list of references, is provided in ASHRAE (2001), Chapter 32.

POTENTIAL ADVANTAGES OF UNDERFLOOR DISTRIBUTION

Although the use of underfloor air distribution is still outside the experience of most North American HVAC designers, the benefits attributed to underfloor air distribution suggest that they will continue to gain in popularity. These benefits include the following:

1) *Significantly reduced building life-cycle costs due to reduced expense associated with occupant "churn".* "Churn" refers to the facility management activities associated with relocating and reconfiguring of worker space. Although the first costs of underfloor air distribution systems are typically higher than conventional overhead distribution, companies are reporting that the incremental investment is quickly re-cooped, even after the first "churn" (Bauman and Webster, 2001). In more cases, underfloor air distribution is considered only after a raised floor system is selected to provide flexible space and cable management. In these cases, if the cost of the raised floor is treated as a sunk cost, an underfloor air distribution system can often yield a net first cost savings, due in-part to reduced ductwork costs.

2) *Significant life-cycle savings due to improved occupant satisfaction and productivity (via improved thermal comfort and indoor air quality).* Recent field research (Bauman, et.al., 1998) indicates that workers without personal (individual) thermal control are half as tolerant of temperature changes as are workers having personal thermal control. Laboratory research has established that active local distribution (small local fan powered distribution boxes) can yield 9ºF to 13ºF (5ºC to 7ºC, floor vs desktop outlets) of occupant personal microclimate control, while passive local distribution (no local fan power) can yield 3ºF to 5ºF (1.7ºC to 3ºC) of personal control (Tsuzuki, 1999). An analysis of previous research concludes that local personal control equivalent to ±5ºF (2.8ºF) can improve group work performance by 3% to 7% (Wyon, 1996), while other research finds that thermal and lighting quality enhancements yield 0.5% to 5% productivity benefits (Fisk, 2000). The life-cycle benefit of these projected gains are huge: e.g. between 10 to 100 times greater than the most optimistic energy-related savings estimates — even approaching the total life-cycle capital and operating costs of the entire facility (Bauman and Webster, 2001). While these estimates of productivity gains are of unknown precision, some amount of benefit seems reasonable. Even the most conservative estimates suggest the likely benefits are significant.

3) *Reduced energy use and cost.* Energy use savings can vary widely in actual underfloor systems but generally result from the following system characteristics: a) increased air-side or water-side economizer potential due to higher supply air temperatures (not always possible, depending on humidity control requirements), b) increased cooling COP due to higher supply air or chilled water temperatures, c) reduced fan energy via reduced fan static due to reduced ductwork, d) reduced fan energy via reduced design flow requirements due to reduced heat gain to the lower occupied region, e) reduced outside air requirements due to improved ventilation efficiency; and f) possible increased indoor cooling temperature setpoints due to occupant choice associated with adaptive comfort control (Bauman and Webster, 2001; Yuan, et. al., 1999; deDear and Brager, 1998).

ISSUES IN THE DESIGN OF UNDERFLOOR AIR SYSTEMS

The following design issues are key to the success of underfloor air delivery systems (order based on the path of air-flow, i.e., coil-related issues first, diffuser placement and design issues last). Each is briefly discussed below.

1) Maintenance of a comfortable dew point (55ºF, 13ºC) in the space while delivering supply air at a drybulb temperature significantly above that point (> 60ºF, 16ºC).
2) Adequate sealing of the floor air plenum at core and window walls and at column covers to prevent bypassing of air to return the plenum
3) Design of underfloor plenum supply to prevent unacceptable temperature rises (<5ºF, 2.5ºC) between plenum supply point and floor registers.
4) Immediate mixing of the supply air at discharge of the floor diffuser to achieve comfortable air temperatures (> 70ºF, 21ºC) within close proximity to the supply diffusers (< 15 in., 0.4 m.).
5) Provision of a terminal and air delivery scheme throughout the occupied space, including near window walls, that will maintain thermostat settings without disrupting naturally occurring temperature stratification.

Controlling Dewpoint
Air handling units for underfloor air delivery must utilize two air streams that will be mixed to provide the supply stream to the space. The first stream includes all of the ventilation air volume and some portion of the return air. It is chilled to a temperature such that when mixed with a second stream, bypassed return air only, provides a dewpoint suitable for comfort (< 53ºF, 11.5ºC). The dual stream approach may be accomplished within the air handler itself, or by separately dehumidifying the outside air supply.

Sealing of the floor plenum
Among the underfloor design issues, sealing of the floor plenum may seem to be least within the computational domain of analysis, yet because of the potential loss to system performance and due to the challenge in achieving it (consider the number of trades involved in building the plenum), it is important to consider. Coordination between the architectural and engineering design disciplines, along with sufficient construction oversight, are required to insure an sufficiently tight plenum. A number of standard architectural details have been field-tested to insure the integrity of the plenum.

Proper supply air temperature
One of the most challenging design problems associated with underfloor air systems is assuring correct supply air leaving the floor diffuser. Because the diffusers are scattered over a large area of the access floor, it is not possible to maintain a uniform temperature. The primary source of heat gain to the plenum supply air is through the structural slab from the return plenum below. With a properly stratified room, temperatures in the return plenum will reach 82ºF (28ºC) or higher. The thermal resistance of a 5 in. (0.125 m.) conventional concrete slab is comparable to that of insulated glass, resulting in significant potential heat gain to the 60ºF (15.5ºC) supply air.

The main variable determining the supply temperature at a particular diffuser is the length of time the air leaving that diffuser has spent in the plenum. That duration is a function of the flow path from the supply plenum inlet to the diffuser. Due to architectural constraints, the open area available for charging the supply plenum is likely to be limited. As a result, air velocity through this inlet opening is likely to be high — as high as 1000 fpm (5 m/s) may be used without excessive noise levels. This momentum admitted to the floor must be dissipated within the plenum because exit velocities from the floor diffusers are so much less (400 fpm, 2.0 m/s). As a result, large scale vortices tend to form within the floor plenum, extending the time the supply air spends in the plenum which increases the heat gain to the supply air that results in excessive supply air temperatures at some of the diffusers (i.e., those whose supply was most affected by the vortices). This phenomenon has been verified anecdotally in the field and in some instrumented mock-ups (Bauman 2000).

Immediate mixing of the supply air at discharge
Currently the most successful methodology for addressing air mixing at the diffuser discharge is the "swirl" diffuser. This diffuser discharges the air into the space in a swirling pattern at a medium face velocity (400fpm, 2.0m/s). Because of the swirling pattern, the diffuser does not form a persistent jet, rather the turbulence at the discharge causes rapid mixing with the room air and sheds momentum through smaller scale transient vortices. Typical air velocities measured 3 ft. (1 m.) above the diffuser are less than 80 fpm (0.4 m/s). These jets do not persist into the occupied torso zone to disrupt the incipient thermal plumes rising from occupants and equipment, so that the desired thermal stratification is not disrupted.

Distribution and design of air delivery scheme
The final design issue discussed here is the provision of an effective perimeter terminal system to achieve temperature control and load tracking without disrupting stratification in the occupied region of a zone. In several projects, variable temperature airflow terminals with updraft slot diffusers at the base of the window wall have provided the requisite control and stratification. For example, at the Alcoa Corporate Headquarters in Pittsburgh (Nall and Hill, 1997), underfloor series flow fan-powered terminals provide a constant volume variable temperature flow stream that responds to space mounted thermostats to control space temperature.

The five underfloor design issues described above are currently the most critical for a successful underfloor air design. Additional underfloor design issues area discussed in Nall (1998). As more buildings are built using underfloor systems, more issues are likely to be identified. Successful evaluation of these issues will require improvements to current energy analysis tools, CFD tools, and rigorous analyses of built conditions, both mock-ups and occupied buildings.

ISSUES IN THE ANALYSIS OF UNDERFLOOR DISTRIBUTION

Due to the dynamic nature of building loads, the most widely used whole building energy analysis and HVAC design simulation tools currently available rely on periodic, usually hourly, time steps (e.g., Trane *TRACE*, Carrier *HAP*, and *DOE-2*). Some less widely used simulation tools rely on shorter time steps (e.g., fifteen minute time steps in *Energy10*). These programs are also designed to capture important longer-term dynamics due to seasonal influences of weather and varying operations by evaluating an entire year (e.g., 8760 time steps in most cases). This large number of time steps necessitates simplifications in other aspects of the modeling in order to maintain a process that is sufficiently time efficient to be useful in the rapid-paced design process.

Unfortunately, several of the most common simplifications found in the currently popular tools and in the new/emerging tools limit the utility of these tools in the design and analysis of underfloor air distribution systems. Three common simplifications are most significant.

1) treating entire air masses in aggregate
2) not predicting interior surface temperatures
3) using simplified radiant exchange modeling for both incoming solar gain and long wave reradiation

Treating air masses in aggregate
The most significant simplification is treating an entire air mass in aggregate, i.e., limiting each HVAC zone or supply air flow to only one air mass node. In effect, this permits the current simulation tools to estimate only one air temperature per HVAC zone or supply air flow, which can be thought of as an average zone or supply temperature. Since conventional overhead distribution systems are designed to provide a well mixed air mass throughout each conditioned zone, an aggregate air mass approach is not a significant limitation for the analysis of overhead distribution systems; however, such a scheme fails to account for stratification which is the most significant feature of underfloor displacement-type systems. Other less significant, but important limitations include the following.

Not predicting interior surface temperatures
The most widely used simulation tools do not predict interior surface temperatures. This limits comfort analysis by requiring that the mean radiant temperature be treated as being equal to the air temperature. This also necessitates the use of constant interior combined convective and radiative heat transfer coefficients.

In underfloor systems, surface temperatures, especially the floor and ceiling, will tend to vary more widely from the average air temperature of the occupied region than in conventional overhead ducted systems with well mixed air masses. This tends to place greater importance on the role of mean radiant temperature in the comfort analysis of spaces served by underfloor systems.

Using simplified static convective/radiative heat transfer coefficients will tend to limit the accuracy of important heat exchange between the surfaces and air masses within the lower occupied and upper unoccupied regions in zones served by underfloor distribution systems.

Simplified radiant exchange modeling
All of the common simulation tools use comparatively simplified radiant exchange modeling for both incoming solar gain and long wave reradiation. In the analysis of underfloor systems, the radiant gains must be analyzed in greater detail in order to better determine which air mass (e.g., occupied or unoccupied) is impacted. For example, being able to predict what surfaces are being struck by direct solar gain and to accurately predict the elevated surface temperature local to that sunlit area is not currently possible with any of the available tools. Rather, the current tools tend to average out these effects over large surface areas. Also, the radiant environment of many building occupants is dominated by the surface temperature of space furnishing (e.g., modular office furniture), rather than the interior and exterior surfaces that bound the whole zone. None of the available tools adequately treat the geometric and thermal complexity of the space furnishings.

The space load determination portions of the most widely used current tools, *TRACE*, *HAP*, and *DOE-2*, derive largely from the same method, the Room Response Factor or "Weighting Factor" method (ASHRAE 1993) which was motivated by the need for computational economy. A unique feature of the space load determination methods in these popular codes is that they do not calculate interior surface temperatures (simplification #2 described above). While the U.S. Department of Energy's emerging new whole building energy analysis tool, *EnergyPlus*, will provide welcome enhancements, its current design substantially addresses only the second limitation (interior surface temperature), leaving the other two limitation unaddressed. This suggests that designers will continue to face a challenge in designing and analyzing the annual whole building performance of underfloor systems.

CURRENT OPTIONS IN THE ANALYSIS OF UNDERFLOOR DISTRIBUTION

Given the limitations of both the current and emerging energy analysis and HVAC design tools, for modeling underfloor air distribution systems, what are the best options currently available for conducting a whole-building analysis of underfloor air distribution systems? Following Hensen (1996), we characterize three broadly differing modeling options:

1) Fully mixed zones, i.e., one-dimensional aggregate modeling of each zone's air mass — using the tools as they were designed (i.e., without "tricking" the programs), this is the only approach currently supported in *TRACE*, *HAP*, *DOE-2*, and *EnergyPlus*.
2) Fully mixed subzones, i.e., dividing the actual HVAC zone vertically into two or more fully mixed subzones — the air mass of each subzone is treated in aggregate, but by modeling two or more subzones, the first order 2-D effects associated with convective intra-zone heat transfer can be approximated. This requires user judgement, external data and/or external modeling (e.g., using CFD) to inform key assumptions (see below).
3) Detailed intra-zonal field approach permitting 2-D or even 3-D solutions of flows and temperatures within the zone via computational fluid dynamics (CFD) methods.

The limitations of the first approach were briefly described in the previous section. The remainder of this paper will be devoted to describing approaches that rely on the second and third approaches.

MODELING BUOYANCY EFFECTS OF UNDERFLOOR SYSTEMS USING CONVENTIONAL BUILDING ENERGY ANALYSIS TOOLS

The most elementary approach to the subzone method (the second method described above) calls for each HVAC zone to be subdivided vertically into a lower (occupied) subzone and an upper (unoccupied) displacement subzone. This subzone approach requires the user to explicitly determine the distribution of internal and solar heat gains between these two subzones and then provide corresponding inputs for each gain source in each subzone. For example, what amount of heat loss from a desktop computer is convectively coupled to the lower occupied air mass versus being transported directly to the upper unoccupied displacement subzone via a convective plume? Further, what portion of the radiant heat loss from the desktop computer loads the ceiling and other surfaces within the upper displacement subzone and thus does not participate in the load on the lower occupied subzone? Similarly, what fraction of the direct solar gain from windows loads the lower occupied air mass and what fraction of the conductive window loads are convected into the upper displacement air mass via convective plumes at the interior window surface?

These assumptions must be provided as model inputs via program commands describing occupants, lighting, internal equipment, fenestration, etc. Clearly, good judgement and reasonable choice for these inputs is key to providing useful results using the currently available simulation tools and must be as well informed as possible. Examples data sources from the literature are discussed below.

Among the current and emerging simulation tools described above, *DOE-2.2* currently provides the greatest flexibility and user control over the key inputs which makes it best suited for practical use in this subzone approach to modeling underfloor air distribution systems. A new input feature in DOE-2.2 is especially useful in this context — the ability to describe these key inputs as algebraic and/or logical expressions, permitting users to treat them as functions of other model inputs, including user-defined input variables. In the *DOE-2.2* program literature, this capability is referred to as input "expressions" and input "parameters". The ability to model these key inputs in the form of algebraic and/or logical expressions enables a user to easily vary the key inputs to determine test the sensitivity of results to their assumed values. This will help a user explore their importance and more readily bound the important assumptions.

As an example, the lower occupied subzone would be modeled as a conditioned zone of variable height (i.e., the subzone height can be input as a user-defined parameter in an expression defining the conditioned zone height). The upper unoccupied displacement zone would be modeled as a return air plenum with height equal to the building floor-to-floor height less the user-defined height of the occupied subzone.

Internal gains from occupants, lights, and internal equipment are input in standard units, e.g., occupied area per person, and lighting or equipment power per unit area (e.g., W/sqft). The distribution of these internal gains can be directed to the occupied or unoccupied subzones using user-defined expressions. These expressions would be based on published data regarding the convective versus radiative split and radiant view factors for each heat gain source (e.g., ASHRAE 2001), and published research which characterize the buoyancy-driven heat transfer between the lower occupied subzone and the unoccupied displacement subzone.

Solar heat gain loading to the two subzones must be controlled based on the amount of glazing assigned to each subzone and the solar transmission and conduction properties of the glazing material. As with the internal gains, this can be facilitated using expressions to distribute the glazing as desired (i.e., literally to specify the dimensions and glazing properties of the windows).

Example data sources for "effective sensible heat gain factors" include Loudermilk (1999) who provides a discussion and recommendations for heat gain factors as a function of occupied mixing subzone height; Brown (2000), who reports a number of example projects which relied, in part, on Loudermilk's data;

Yuan, Chen, and Glicksman (1999) who characterize sensible heat factors based on parametric CFD analyses; and Zweifel and Koschenz (1993) who report heat gain factors based on a detailed displacement ventilation model.

Assuming common conditions for air flow and mixed zone height, these sources recommend an overall "split" between the lower occupied and upper unoccupied subzones that ranges from 1/3-2/3 (i.e., 1/3 of space internal heat gain loads the lower subzone, 2/3 loads the upper subzone) to 2/3-1/3 (i.e., 2/3 of space internal heat gain loads the lower subzone, 1/3 loads the upper subzone). Yuan, et.al (1993) and Zweifel and Koschenz (1993) recommend overall splits close to 1/3-2/3 while Loudermilk (1999) and Brown (2000) recommend and use overall splits close to 2/3-1/3. As indicated above, the expressions input capability of *DOE-2.2* allows the user to easily explore the sensitivity of modeling results across a range of assumptions and operating conditions.

MODELING OTHER DESIGN AND PERFORMANCE ISSUES OF UNDERFLOOR SYSTEMS USING CONVENTIONAL BUILDING ENERGY ANALYSIS TOOLS

Controlling Dewpoint

The dual air path and dual coil configuration of many underfloor systems cannot be directly modeling in any of the currently available whole building energy analysis simulation tools. Undoubtedly, future tools will provide users with more modular, component-based modeling capabilities. Among the current tools, the first order energy effects of dual air path / dual coil configurations can only be approximated using a "dummy" system serving a dummy zone which treats the outside air. This approach fails to explicitly consider the psychrometrics of the mixed air streams.

Proper supply air temperature

The aggregate air mass simplifications described above, as they are applied to zone air masses, are also applied to supply air streams. Only *DOE-2.2* and *EnergyPlus* permit users to explicitly model thermal exchange between supply ducts and the zones through which they pass. A first order approximation of the losses from (gains to) the supply plenum, can be obtained by describing the UA associated with the plenum. Unfortunately, this approach neglects the mass effects of the structural floor slab.

The remaining underfloor design issues identified previously can not be modeled using the currently available whole building energy analysis simulation tools due to the simplification of aggregate air masses. These additional design issues can be treated using steady-state CFD models. These are discussed and illustrated in the following section.

MODELING DESIGN ISSUES OF UNDERFLOOR SYSTEMS USING CFD

Proper supply air temperature

Computational fluid dynamics (CFD) has been used to investigate strategies to achieve proper supply air temperature at all diffusers (i.e., by overcoming the formation of large scale vortices in underfloor supply plenums). CFD simulation outputs for two different underfloor plenum supply schemes are presented below (Figures 1 and 2). The first (Figure 1) shows a simplified approach using multiple supply points to the underfloor plenum from the mechanical core (the large white area in the upper right corner of Figures 1 and 2), each with a face velocity of about 1000 fpm (5 m/s) and relatively laminar flow. The large dark areas in Figure 1 indicate the warmest regions of supply air in the undefloor plenum, and correspond to the regions of large vortices caused by the relatively high velocity laminar discharge into the underfloor plenum. The vortices are formed to dissipate the momentum of the supply air, creating excessive air path lengths which result in excessive heat gain from the return plenum. Air supplied through floor diffusers (the small black squares in Figure 1) within these large vortex regions will be too warm to provide adequate local cooling.

An alternate strategy is to introduce supply air into the plenum in two different flow regimes (Figure 2). Directional jets are utilized to throw a portion of the supply air from the core to the farthest perimeter diffusers (e.g., the darken area in Figure 2 emanating diagonally from the mechanical core). The remainder of the supply air is introduced to the plenum through highly turbulent, deflecting diffusers (e.g., the darkest bi-directional areas emanating from the mechanical core). The effect of these diffusers in the underfloor supply plenum is similar to that of the swirl diffusers in the room, i.e., the air adjacent to the plenum inlet is quickly mixed with the incoming supply, and no jets persist distant from the mechanical core. Face velocity of the inlet can be kept high to minimize the area of the supply opening to the plenum, yet the viscous effects of the turbulent flow at the diffuser face dissipates the momentum of the incoming air rapidly enough to defeat the formation of large scale vortices.

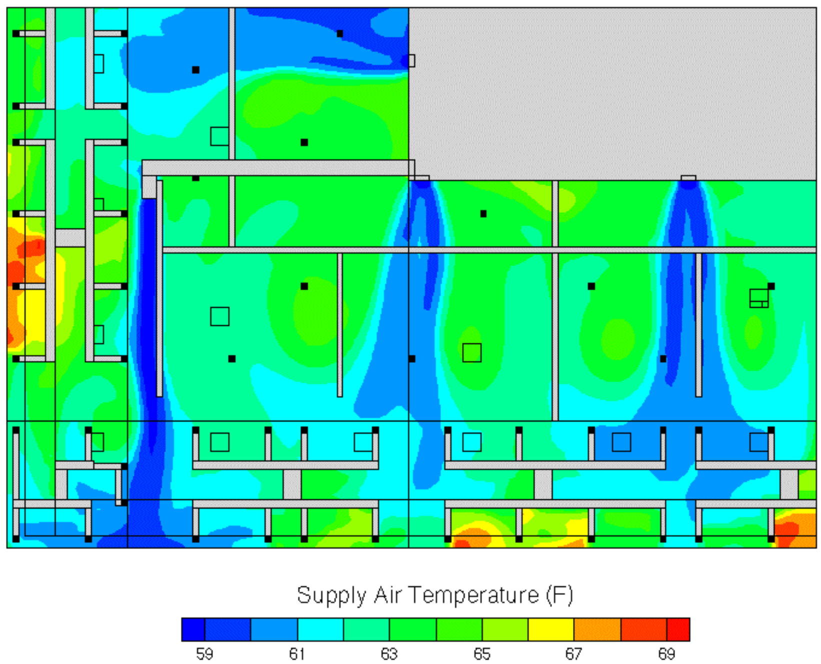

Figure 1. CFD Study of Laminar only Supply to Underfloor Plenum

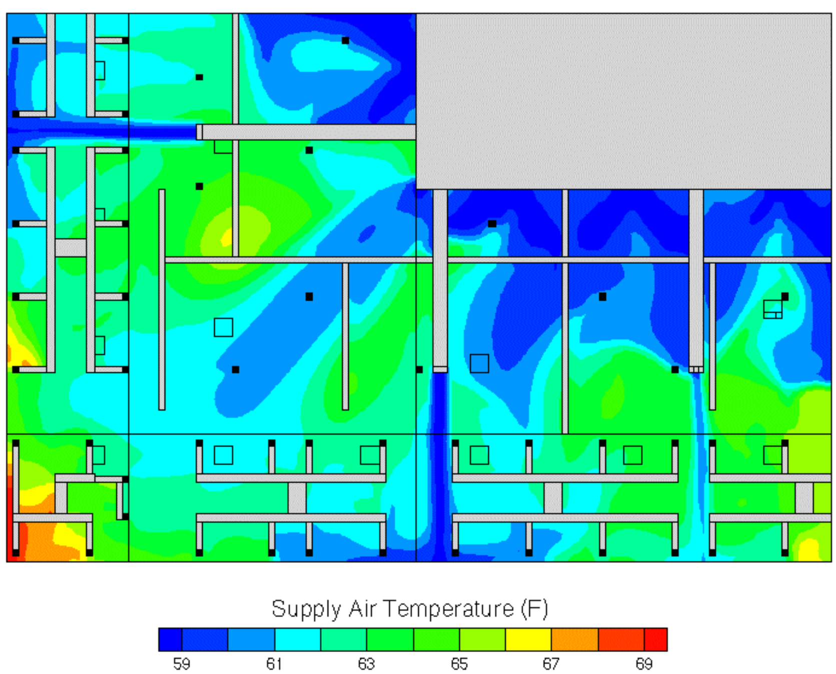

Figure 2. CFD Study of Laminar/Turbulent Supply to Underfloor Plenum

Distribution and design of air delivery scheme

CFD can also be used to investigate strategies for perimeter terminal system design to achieve effective temperature control while maintaining stratification in the occupied region of a zone. In the Alcoa Corporate Headquarters described previously, the face velocity of the continuous slot diffusers at the foot of the 12 ft. (3.75 m.) floor-to-ceiling glass window wall was optimized at 375 fpm (1.9 m/s) using trial-and-error CFD simulations for both design heating and cooling conditions. Below is a CFD comfort parameter (PPD) study of this flow at a cooling design condition (Figure 3), showing the impact of exterior horizontal overhang placement with and without an interior light shelf. The upper image represents overhang only; the lower represents the selected overhang with light shelf configuration (the window wall, light shelf and overhang are at the right; the objects in the center of each image represent an occupant working at a computer terminal).

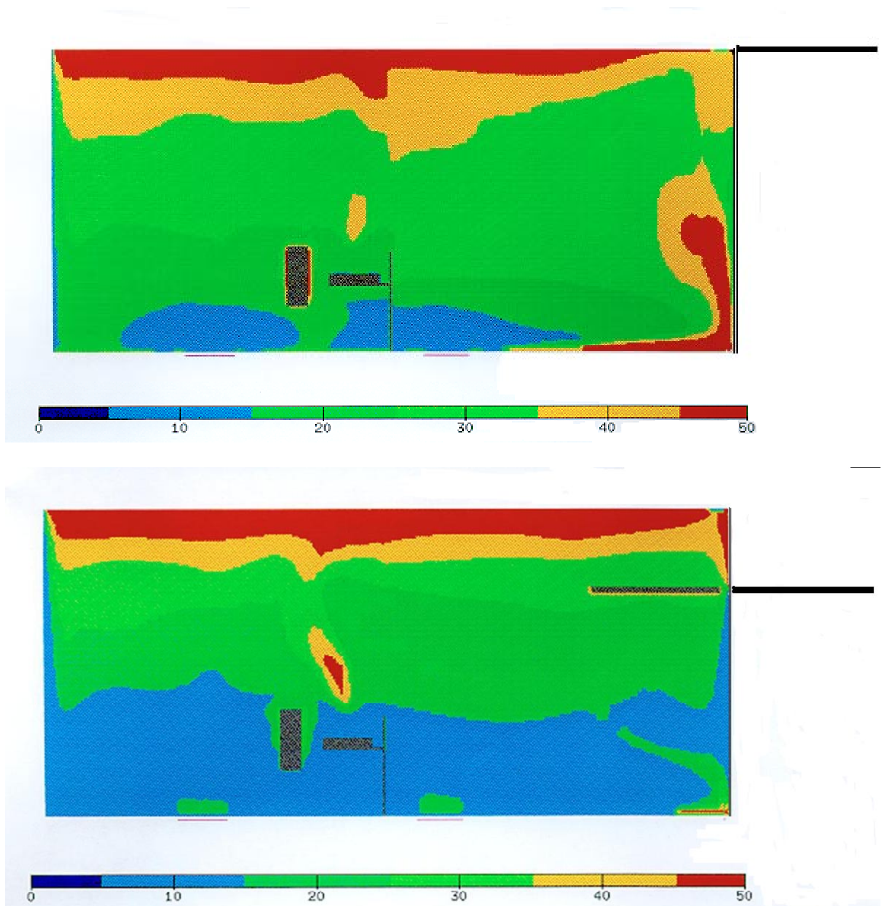

Figure 3. CFD Study of PPD Distribution for the Alcoa Corporate Headquarters Perimeter Zone

The continuous updraft slot diffuser at the perimeter tends to entrain the convective plume rising from the solar heated carpet adjacent to the window wall. A continuous return slot at the head of the window provides an opportunity to remove the resulting warm updraft from the occupied space. In a heating situation, the warm updraft from the slot diffuser counters the convective downdraft on the cold glass surface, preventing the cold draft from rolling out onto the occupied floor.

Immediate mixing of the supply air at discharge

CFD methods can also be useful to investigate the mixing of supply air in the immediate vicinity of the supply registers and to generally assess the temperature gradient of the occupied region. Simplified models of floor diffuser may be constructed in a CFD analysis by using trial and error to replicate instrumented results of diffuser test chamber behavior for isotherms. Variables manipulated include turbulent intensity, face velocity, spin, number and vector of individual jets in the model. After diffuser behavior from test chamber results is replicated with the CFD simplified model, these can be treated as model components and placed into larger models of room space to test impact of diffuser performance on system performance and stratification. This process was followed by Nall and Hill (1997) to select diffusers.

SUMMARY OF DEVELOPMENTS NEEDED IN EXISTING TOOLS

The current and new whole building energy analysis and HVAC design simulation tools employ several simplifications that currently limit their utility for the design or analysis of underfloor air distribution systems. Chief among these simplifications is treating an entire HVAC zone air mass in aggregate (i.e., one average air temperature per zone). Other simplifications include not predicting indoor surface temperatures, using simplified radiant exchange modeling for both incoming solar gain and long wave reradiation, and the ability to flexibly configure air-side system components to model innovative systems such as dual path / dual coil configurations.

While the U.S. Department of Energy's new *EnergPlus* simulation program addresses one of these important simplifications (surface temperatures for simplified interior geometries), the remaining simplifications must also be addressed before the annual energy performance of underfloor air distribution systems can be conveniently modeled. In the meantime, the lack of capable and convenient tools will hamper both the adoption and reliable use of underfloor air distribution.

An obvious direction for future development would be the integration of CFD analysis for design with periodic modeling for energy performance. Recent work is indicative of a growing body of research investigating these issues (Rees and Haves, 1999, Maliska, 2001, Broderick and Chen, 2001, Beausoleil-Morrison, 2001, and Beausoleil-Morrison, et al., 2001).

REFERENCES

ASHRAE. 1993. *Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta.

ASHRAE. 2001. *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta.

Bauman, F., T. Carter, A. Baughman, and E. Arens. 1998. "Field study of the impact of a desktop task/ambient conditioning system in office buildings", *ASHRAE Transactions*, 104(1).

Bauman, F. 2000. Private communication. Center for the Built Environment, University of California, Berkeley.

Bauman, F. and T. Webster, 2001. "Outlook for Underfloor Air Distribution", *ASHRAE Journal*, June 2001, 18-27.

Beausoleil-Morrison, I. 2001. "The adaptive coupling of computational fluid dynamics with whole-building thermal simulation", *Proceedings of Building Simulation 2001*, p1259

Beausoleil-Morrison, I., J. Clarke, J. Denev, I.A. Macdonald, A. Melikov and P. Stankov. 2001. "Further developments in the conflation of CFD and building simulation", *Proceedings of Building Simulation 2001*, p1267

Broderick, C. and Q. Chen. 2001. "A simple interface to CFD codes for building environment simulations", *Proceedings of Building Simulation 2001*, p577

Brown, M. 2000. "Underfloor air conditioning systems: principles and applications*", Carrier Global Engineering Conference, 2000.*

DeDear, R. and G. Brager, 1998. "Developing and adaptive model of thermal comfort and preference", *ASHRAE Transactions*, 104(1a), 145-167.

Faulkner, D. W.J. Fisk, and D.P. Sullivan. 1995. "Indoor airflow and pollutant removal in a room with floor-based task ventilation: results of additional experiments", *Building and Environment*, 30(3), 323-332.

Fisk, W. 2000. "Health and productivity gains from better indoor environments and their relationship with energy efficiency", LBNL-45484, Lawrence Berkeley National Laboratory.

Hensen, et.al, 1996. "Modeling Approaches for Displacement Ventilation in Offices", *Proceedings of the 5th International Conference on Air Distribution in Rooms, ROOMVENT '96*, (http://www.esru.strath.ac.uk/publications/roomvent.htm)

Loudermilk, K. 1999. "Underfloor air distribution solutions for open office applications", *ASHRAE Transactions*, 105(1).

Maliska, C. 2001. "Issues on the integration of CFD to building simulation tools", *Proceedings of Building Simulation 2001*, p29.

Nall, D. 1998. "Underfloor Air Delivery System", The Construction Specifier, *The Construction Specification Institute*, February, 45-48.

Nall, D. and J. Hill. 1997. "Utilization of Computational Fluid Dynamics to Design HVAC Systems and the Building Envelope for a Corporate Headquarters Building", *The 21st Century Outlook*, AIA, U.S. Green Building Council.

Rees, S., P. Haves. 1999. "A nodal model for displacement ventilation and chilled ceiling systems in office spaces". *Proceedings of Building Simulation '99*, 433-440.

Tsuzuki, K, et al.1999. "Individual thermal comfort control with desk-mounted and floor-mounted task/ambient conditioning (TAC) system", *Proceedings of Indoor Air 99*, (2), 368-373.

Wyon, D. 1996. "Individual microclimatic control: required range, probable benefits and current feasibility", *Proceedings of Indoor Air 96*, (1), 1067-1072.

Yuan, X., Q, Chen, and L. Glicksman. 1999. "Performance evaluation and design guidelines for displacement Ventilation", *ASHRAE Transactions*, 105(1)

Zweifel, G. and M. Koschenz, 1993. "Simulation of displacement ventilation and radiant cooling with DOE-2", *ASHRAE Transactions*, 99(1), 548-555.