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ENERGY PERFORMANCE OF UNDERFLOOR AIR DISTRIBUTION SYSTEMS

PIER FINAL PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

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University of California, Berkeley
University of California, San Diego
Lawrence Berkeley National Laboratory

April 2007
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Prepared For:
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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Performance of Underfloor Air Distribution Systems is the final report for the Energy Performance of Underfloor Air Distribution Systems project (contract number 500-01-035) conducted by the Center for the Built Environment, University of California, Berkeley; University of California, San Diego; and Lawrence Berkeley National Laboratory. The information from this project contributes to PIER's Building End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

Table of Contents

List of Figures

Prepared for the California Energy Commission, April 2007 11 https://escholarship.org/uc/item/1pm8b02s

List of Tables

Abstract

This multi-year project developed EnergyPlus/UFAD, a version the publicly available whole-building energy simulation program EnergyPlus that adds the capability for modeling underfloor air distribution systems. The project also developed a practical design tool for determining the cooling airflow quantity for underfloor air distribution systems. EnergyPlus/UFAD and the cooling airflow design tool are the first validated underfloor air distribution system tools of their kind. As such, they represent a significant advance in the state of the art of the design and energy analysis of such systems. This highly collaborative effort involved experts and facilities from four organizations, including the Center for the Built Environment at University of California, Berkeley; University of California, San Diego; Lawrence Berkeley National Laboratory; and York International.

This final report and seven appendices present experimental testing and analytical and computational fluid dynamics modeling on room air stratification and underfloor plenum distribution—critical efforts that informed the development of models for EnergyPlus. Also discussed are new implementations of heating, ventilation, and air conditioning systems to support underfloor air distribution system modeling in EnergyPlus and the development of a practical design tool for such systems.

Keywords: underfloor air distribution, UFAD, EnergyPlus, EnergyPlus/UFAD, energy modeling, design tool, room air stratification, cooling load, underfloor plenum, full-scale experiments, salt-tank testing, thermal plumes, thermal comfort

Executive Summary

Introduction

In 2002, underfloor air distribution (UFAD), an innovative and relatively new space conditioning technology, was experiencing rapid growth in North America. UFAD uses the open space between a raised floor and a structural concrete slab to deliver conditioned air directly into the occupied zone of the building, most commonly through floor-level supply outlets. UFAD's growth, which continues today, was driven by the broad range of potential benefits that well-designed UFAD systems offer over conventional overhead (OH) air distribution systems:

- Increased flexibility and reduced life-cycle costs through the use of a raised access floor system
- Improved thermal comfort by allowing individual employees control over nearby floor diffusers
- Improved ventilation effectiveness and indoor air quality (IAQ) by delivering fresh supply air through floor diffusers close to occupants
- Reduced energy use through a variety of strategies particularly well-suited to mild California climates
- Improved employee satisfaction and productivity by giving occupants greater control over their local environment and by improving the quality of indoor environments

However, UFAD systems were being designed and installed even before some of the most fundamental performance aspects were understood or characterized, and standardized methods and guidelines for designing these systems or optimizing their performance were not available.

Purpose

This project produced tools to help designers create energy efficient and effective UFAD systems and improve understanding in two key areas where important differences exist between the energy performance of UFAD and that of conventional OH air distribution systems:

- Room air stratification (RAS)—or how the temperature of the air in a conditioned space stratifies with height
- The thermal performance of underfloor plenums, or the temperature and velocity of air flowing between the raised floor and the concrete slab

Objectives

- Provide a sound theoretical understanding of the behavior of UFAD systems by conducting laboratory-, bench-, and full-scale experiments.
- Develop validated mathematical models of the RAS phenomenon and the thermal performance of underfloor air supply plenums.
- Integrate the RAS and underfloor plenum models, along with other system upgrades, into the EnergyPlus whole-building energy simulation program, to allow design professionals and others to simulate UFAD system energy performance.
- Develop a practical design procedure for determining the amount of conditioned air required during cooling operation of a UFAD system.

Significant Findings

The work done under this project generated significant insights into the performance and operation of UFAD systems. Highlights are described below:

- By providing validation-quality data under operating conditions that closely mimicked real world conditions, full-scale RAS tests were critical to the development of the RAS model for EnergyPlus/UFAD. These tests also provided an opportunity to investigate a range of design parameters, develop RAS performance correlations based on these parameters, and compare results with the more idealized small-scale salt tank tests.
- The more limited, yet still extremely valuable, salt tank testing produced two key findings:
    - Determination of the "interface height" separating the cooler occupied zone and warmer upper zone—the two zones in the simplified model of a stratified UFAD environment
    - Characterization of the impact on RAS performance of multiple diffusers, multiple (point source) plumes representing interior zones, and larger window plumes representing perimeter zones
- An RAS model characterized the difference in temperatures between the floor and the ceiling by dividing the space into the lower and upper zones described above, each represented by a single temperature. While oversimplifying real stratification, this scheme captures first order effects well and is simple enough for use in EnergyPlus.
- Underfloor plenum experiments provided validation-quality data under realistic full-scale conditions to support the development of a computational fluid dynamics (CFD) plenum model. The plenum tests also demonstrated the complex nature of the airflow and thermal performance of underfloor plenums. Key design and operating parameters that can impact plenum performance include inlet velocity, temperature, and direction; number and location of inlets; total flow rate; air leakage; and the amount of stratification in spaces above and below plenum.
- Despite the complexity of the plenum airflow and heat transfer processes, the plenum energy balance predicted by CFD work agreed within 10% of the experimental data.

This result supported the approach of using a simplified, well-mixed plenum model to provide reasonable estimates of overall plenum energy performance. The validated CFD plenum model simulated a broader range of plenum design and operational parameters, creating an expanded numerical database that was used to derive the final form of the simplified underfloor plenum model for use in EnergyPlus.

- During early meetings, the research team discovered that, due to the existence of a cool underfloor supply plenum in a multi-story building, several new heat transfer pathways became important considerations in a stratified UFAD environment. A simplified first-law model was therefore used to estimate and compare the relative magnitudes of the heat being removed from a room through two primary pathways:
    - Heat extraction via warm return air exiting the room at ceiling level or through the return plenum
    - Heat entering the underfloor supply plenum either through the slab from the floor below or through the raised floor panels from the room above

  Surprisingly, results for typical multi-story building configurations (raised access floor on structural slab with or without suspended ceiling) showed that 30–40 percent of the total room cooling load is transferred into the supply plenum and only about 60–70 percent is accounted for by the return air extraction rate. These findings have important implications for the design, operation, and energy analysis of UFAD systems.

Results

On the basis of these and other findings, the team added new and enhanced modeling capabilities to EnergyPlus:

- RAS models for both interior and perimeter zones
- An underfloor plenum model
- Heating, ventilating, and air conditioning (HVAC) system model upgrades (including a variable-speed fan terminal unit and return air bypass capability) to allow simulation of typical UFAD system configurations

The resulting program, EnergyPlus/UFAD, allows designers to calculate the energy use of UFAD systems and compare the performance of UFAD and conventional systems. EnergyPlus/UFAD is the first validated whole-building energy simulation program of its kind and is available from the public EnergyPlus website maintained by U.S. Department of Energy (DOE): www.energyplus.gov.

The project also developed a practical and simplified design procedure for determining the amount of conditioned air required during cooling operation of a UFAD system. In its final form, this spreadsheet-based calculation procedure will be easy to use by practicing design engineers. The calculation engine was developed based on empirical correlations derived from the RAS full-scale testing database, and currently includes three diffuser types. The design tool predicts a range of acceptable cooling airflows, within which the target comfort criteria are satisfied for the design input assumptions of the model.

Conclusions

EnergyPlus/UFAD and the UFAD design tool represent a significant advance in the state of the art of UFAD design and analysis. Further, the coordinated approach has proven to be very successful, as the EnergyPlus validation studies completed to date have demonstrated good agreement with experimental and CFD-predicted data. In addition, the large amount of supporting research conducted has produced a vast amount of new knowledge and improved understanding of the fundamental principles of UFAD system design, operation, and energy performance.

Recommendations

In this ground-breaking work, not all model development goals were achieved to a level of accuracy and validity originally envisioned at project start. Recommended activities to improve and refine EnergyPlus/UFAD include the following:

- Complete refinement of interior zone RAS model
- Complete refinement of perimeter zone RAS model
- Complete the validation of both the improved interior and perimeter RAS models using data from full-scale testing
- Implement updated models in EnergyPlus/UFAD
- Update engineering documentation of EnergyPlus/UFAD

Recommended activities to support the cooling airflow design tool include the following:

- To support the development and refinement of supplemental calculations and assumptions in the design tool, use the improved version of EnergyPlus/UFAD to simulate a prototype commercial office building.
- Add more capabilities to the design tool
- Develop a suitable user interface for the spread-sheet based design tool
- Use available field data collected through ongoing commissioning and energy use case studies to conduct a comparison and validation of the design tool

Benefits to California

As an example of UFAD's potential benefits in California, where UFAD use is growing, the team estimated the HVAC energy savings for UFAD in one sector, large offices, over the next 10 years. For UFAD penetration, the team assumed that the growth rate would continue to reflect the rates since 1999, as well as the following:

- Overall new construction growth rate: 2% per year, constant
- Fan energy savings: 22%, based on a previous study of fan savings (Webster 2000)
- Economizer savings: 15% and 30%

The team ignored potential chiller savings, since data are lacking as to the magnitude and since the proportion of chilled water systems is less than 40% even in large buildings. Economizer savings of 30% are based on a model that uses Oakland weather data for a typical meteorological year; less benign climates are assumed to yield 15% savings.

New construction for the estimate includes both retrofit and new buildings, since the team's estimate for penetration is based on annual sales of raised floor panels with an unknown breakdown between the two. However, based on the CBE Case Studies project, the team estimates that 25% of new UFAD projects are retrofits to existing facilities. The teams used as the baseline (without escalation) the California commercial end-use energy use intensities for ventilation and cooling and the aggregate floor areas for large offices, as provided by PIER.

The values shown in Table ES-1 represent the estimated potential energy savings expressed as a percent of the overall HVAC energy use for all new construction of large offices (based primarily on a building stock of conventional systems). As shown, UFAD could reduce energy use in new large office buildings by almost 25% in 2010 and more than 50% by 2015.

Table ES-1. Percent savings in HVAC energy for large office building new construction for given UFAD market penetrations

	% Energy Savings by Year		
	2005	**2010**	**2015**
UFAD projected penetration rates in large new offices	6%	24%	53%
% of HVAC energy with 15% economizer savings	1%	4%	10%
% of HVAC energy with 30% economizer savings	2%	6%	14%

Additional benefits to California based on the results of this project are listed below:

- Improve the effectiveness of building design and construction practices by providing validated energy simulation and design tools that optimizes the energy and cost effectiveness of UFAD systems.
- Help policymakers establish methodologies in future releases of Title-24 that allow proper receipt of credits on projects that implement UFAD in an energy-conserving manner by providing an updated and clearer picture of the potential energy use benefits of UFAD systems.
- Improve the health and safety of building occupants by establishing a database of test information that could be used to analyze thermal comfort of UFAD systems and assist with future studies of ventilation effectiveness.
- Increase customer choices for efficient operation of buildings by providing standardized design and analysis tools and technical knowledge that would reduce the risk to practitioners and owners when choosing to implement UFAD technology.
- Encourage the rapid incorporation of research findings into UFAD products by working closely with UFAD industry leaders, including York International, a partner on this project, and other major HVAC manufacturers who are members of CBE.

1.0 Introduction

1.1. Background and Overview

Underfloor air distribution (UFAD) 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 5–10 years because it offers abroad range of potential benefits over conventional overhead air distribution systems. Specifically, well-designed UFAD systems can improve thermal comfort, improve indoor air quality (IAQ), reduce energy use, improve worker satisfaction and productivity, increase flexibility, and reduce life-cycle costs over conventional practice (Bauman and Webster 2001; Bauman 2003).

Despite the growing use of UFAD systems, UFAD is still a relatively new and unfamiliar technology to the building industry at large. In 2002, when this project was starting, standardized methods and guidelines for designing these systems or optimizing their performance were not available. Furthermore, UFAD systems were being designed and installed at an increasingly rapid pace, even before a full understanding and characterization of some of the most fundamental aspects of UFAD system performance were in place. In the original proposal for this project, the team identified a strong need for an improved fundamental understanding of several key energy performance features of UFAD system design. These issues are described briefly below:

- **Room air stratification (RAS).** Under cooling operation, properly controlled UFAD systems produce temperature stratification in the conditioned space. What are the combinations of supply air temperature and volume, and heat loads for both interior and perimeter building zones that provide acceptable thermal comfort in the occupied zone? What impact do the type and number of supply diffusers have on the stratification performance? An understanding of controlled/optimized thermal stratification is critical to provide designers with a reliable energy-estimating tool as well as a sound basis for developing design tools and guidelines. Although some preliminary UFAD cooling airflow design methods have been described (Loudermilk 1999; Bauman 2003), design engineers often cite methods for airside design sizing as one of the most important unanswered questions regarding UFAD system design.
- **Underfloor air supply plenum.** An important difference between conventional and UFAD system design is that cool supply air flowing through the underfloor plenum is exposed to heat gain from both the concrete slab (conducted from the warm return air on the adjacent floor below the slab) and the raised floor panels (conducted from the warmer room above). The magnitude of this heat gain can be quite high, resulting in undesirable loss of control of the supply air temperature from the plenum into the occupied space (sometimes referred to as thermal decay). These warmer supply air temperatures can make it more difficult to maintain comfort in the occupied space

(without increasing airflow rates), particularly in perimeter zones where cooling loads reach their highest levels.

- **Whole-building energy performance.** At the time this project was initiated, the industry lacked a validated whole-building energy simulation program capable of accurately modeling UFAD systems. In combination with the above described cooling airflow design tool, such an energy modeling capability was the top technology need widely identified by system designers and other UFAD technology experts and users. Furthermore, from the perspective of California Title-24 policymakers, the development of an energy-modeling capability for UFAD systems would help establish methodologies to allow proper receipt of credit for projects that implement UFAD in an energy-conserving manner.

1.2. Project Objectives

The goal of this project was to develop UFAD system simulation software to allow design practitioners to calculate the energy performance of UFAD systems and compare the performance of UFAD systems with that of conventional systems. The availability of such a tool would help UFAD technology achieve its full potential by enabling the design of UFAD systems that are energy efficient, intelligently operated, and effective in their performance.

The objectives of this project were as follows:

- Provide a sound theoretical understanding of the behavior of UFAD systems by conducting laboratory-, bench-, and full-scale experiments.
- Develop validated mathematical models of the RAS phenomenon and the thermal performance of underfloor air supply plenums.
- Integrate the RAS and underfloor plenum models, along with other system upgrades, into the EnergyPlus whole-building energy simulation program. The final product will be a version of EnergyPlus, called EnergyPlus/UFAD that can be used by design professionals and others to simulate UFAD system energy performance.
- Develop a practical design procedure for determining the amount of conditioned air required during cooling operation of a UFAD system.

1.3. Report Organization

The work performed under this project is described in one main report and several appendices, as outlined below.

- **Part I: Final Report, Project Summar**y: This report provides an overview of the project with shorter summaries of the major project outcomes from each of the other five larger parts of the final report.
- **Appendix A. Part II: Room Air Stratification Full-Scale Testing:** This report describes the methodology, results, and analysis of the RAS experiments conducted in the York full-scale test chamber using commercially available floor diffusers in a realistic office configuration. These tests provided validation quality data to support the development

of the RAS Model for EnergyPlus and also allowed the investigation of a wide range of practical design parameters for UFAD systems.

- **Appendix B. Laboratory Layouts and Normalization Room Air Stratification Profiles**
- **Appendix C. Part III: The Fluid Dynamics of an Underfloor Air Distribution System**: This report represents the PhD thesis for Qing Liu of University of California, San Diego (UCSD) and describes the methodology, results, and analysis of the RAS experiments conducted in small-scale salt-water tanks. These tests provided validation quality data and an improved fundamental understanding of UFAD fluid dynamics to support the development of an analytical model of RAS performance. This report also describes the development of a simplified RAS model for implementation in EnergyPlus.
- **Appendix D. Part IV: Underfloor Plenum Testing and Modeling**: This report describes the methodology, results, and analysis of experiments conducted in a full-scale underfloor plenum test facility. These tests provided data for validation of a computational fluid dynamics (CFD) model of the underfloor plenum. This report also describes the use of the CFD plenum model to develop a simplified plenum model for implementation in EnergyPlus.
- **Appendix E. Part V: EnergyPlus Module Development and Validation**: This report describes the engineering documentation for the new version of EnergyPlus capable of modeling UFAD, called EnergyPlus/UFAD. It describes incorporation of the above-described RAS model and plenum model; new heating, ventilating, and air conditioning (HVAC) system model upgrades to accommodate UFAD systems; and preliminary validation results.
- **Appendix F. Part VI: UFAD Cooling Airflow Design Tool**: This report describes the development of a practical and simplified design procedure for determining the amount of conditioned air required during cooling operation of a UFAD system.

2.0 Project Approach

This project was a coordinated, multi-institutional effort among the following organizations:

- Center for the Built Environment (CBE), University of California, Berkeley (UCB): Project lead, full-scale testing, RAS model development, underfloor plenum testing and modeling, model validation.
- Department of Mechanical and Aerospace Engineering, University of California, San Diego (UCSD): Salt tank testing, RAS model development, model validation.
- Lawrence Berkeley National Laboratory (LBNL): System upgrades to EnergyPlus, model validation, EnergyPlus/UFAD software implementation and engineering documentation.
- York International, York, Pennsylvania: Full-scale testing.

Figure 1 shows a schematic diagram of the project organization. As shown, development of the underfloor plenum model was supported by full-scale testing to provide model validation. Development of the room air stratification model was supported by small-scale salt tank testing to improve theoretical understanding and full-scale laboratory testing to provide realistic data for comparison and model validation. These two significant new modeling capabilities were incorporated into EnergyPlus. In addition, the project made selected upgrades to the HVAC modeling capabilities in EnergyPlus to accommodate typical HVAC configurations of UFAD systems. All groups participated in model validation.

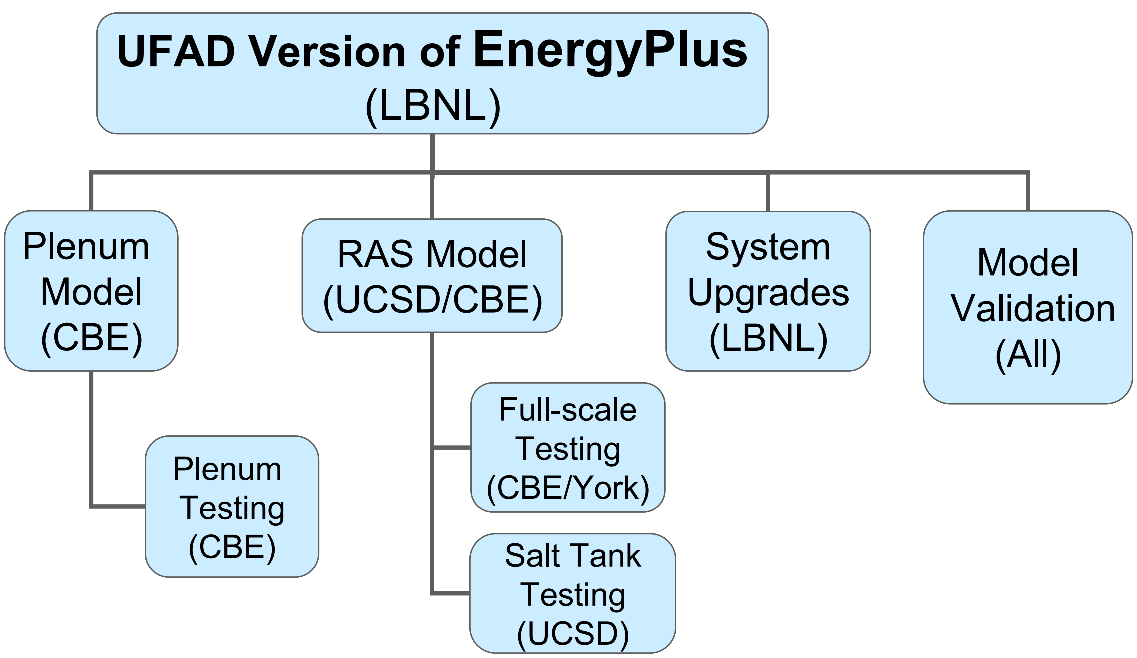

Figure 1. Schematic diagram of the project organization

The major technical tasks included in the project work scope are discussed in the subsections below.

2.1. Task 2.1: RAS Full-Scale Testing

The objective of this task was to characterize the impact of various UFAD technology design and operating parameters on RAS. To accomplish this goal, researchers conducted experiments in the York full-scale test chamber using commercially available floor diffusers in a realistic office configuration. Parameters and issues investigated follow:

- Diffuser type
- Supply air temperature
- Supply air volume
- Performance differences between variable and constant volume system designs
- Comparison of UFAD to overhead system airflow requirements
- Comparison of performance in perimeter vs. interior zones

This task provided a sound theoretical understanding of UFAD system performance, developed empirical correlations that describe stratification performance where possible, and provided validation quality data under realistic full-scale conditions to support the development of the RAS Model.

2.2. Task 2.2: Salt Water Tank Testing

This task had two objectives:

- Gain a more accurate understanding of the airflow patterns and temperature stratification produced by UFAD systems.
- Validate the salt-water tank model, using the full-scale test data collected in Task 2.1 This step is important because the laboratory model is less expensive and more readily accessible than is the full-scale model and therefore presents an effective means to further study the fluid mechanics of UFAD systems.

To accomplish these objectives, the researchers conducted salt-water laboratory simulations of an UFAD system. The laboratory experiments were first used to identify the important physics to incorporate into the analytical model. This task provided a sound theoretical understanding of UFAD system performance and validation quality data to support the development of the RAS Model.

2.3. Task 2.3: Underfloor Plenum Testing

The objective of this task was to provide improved understanding of how supply air temperature varies with plenum configuration and distance traveled through the plenum. To this end, researchers investigated energy performance issues by conducting experiments in the CBE full-scale underfloor air supply plenum test facility. These experiments studied the heat exchange between the exposed concrete structural slab, raised floor panels, and the supply air as it flows through the underfloor plenum. This task provided a sound theoretical understanding of the airflow and thermal performance of underfloor air supply plenums and validation quality data under realistic full-scale conditions to support the development of the underfloor plenum model.

2.4. Task 2.4: RAS Model Development

The objective of this task was to provide a method to calculate the room air flow and temperature stratification resulting from UFAD system designs. To this end, researchers developed a RAS Model for the UFAD system based on a simplified zonal model suitable for implementation into EnergyPlus. The two-zone model was deemed appropriate, as it was readily implemented and captured the essential features of the stratification. The model was developed using insights gained from the salt-water tests (Task 2.2), CFD, and full-scale testing results (Task 2.1).

2.5. Task 2.5: Underfloor Plenum Model Development

The objective of this task was to provide a method to calculate the thermal performance of underfloor air supply plenums. The model developed used a simplified approach suitable for implementation into EnergyPlus. The model was developed using the generated databases as well as insights gained from both the full-scale Underfloor Plenum Model Testing (Task 2.3) and the associated CFD analysis.

2.6. Task 2.6: EnergyPlus Module Development and Validation

The objective of this task was to produce UFAD system simulation software to enable design practitioners to calculate the energy use of UFAD systems and compare the performance of UFAD systems with conventional systems. To this end, the researchers incorporated the RAS Model developed in Task 2.4 and the underfloor plenum model developed in Task 2.5 into EnergyPlus, and upgraded the EnergyPlus HVAC system model as needed to allow simulation of typical UFAD system configurations. The resulting EnergyPlus RAS and underfloor plenum modules were validated against RAS measurements made in Task 2.1 in the York full-scale test chamber and against plenum measurements made in Task 2.3 in the CBE Underfloor Air Supply Plenum test facility.

2.7. Task 2.9: Cooling Airflow Design Tool Development

The objective of this task was to develop a practical and simplified design procedure for determining the amount of conditioned air required during cooling operation of a UFAD system in both interior and perimeter zones. To this end, the researchers carefully analyzed the RAS full-scale testing database from Task 2.1, the salt water tank testing database from Task 2.2, and the underfloor plenum testing database from Task 2.3. The design tool was reviewed and evaluated by practicing engineers to ensure its usefulness and validated to the extent possible by comparison with experimental results from Task 2.1 and EnergyPlus simulation results from Task 2.6.

3.0 Project Outcomes

3.1. RAS Full-Scale Testing

This section summarizes the results of full-scale RAS testing conducted to provide a detailed understanding of how room air stratification is influenced by various design and operating conditions in typical office arrangements. These experiments were designed and conducted by CBE in a laboratory facility provided by York International in York, Pennsylvania.

3.1.1. Facility Layout and Construction

The facility consists of a test chamber, an adjoining conference room, and an environmental chamber (EC). Air handling equipment is located inside the warehouse adjacent to the EC; chillers are located outside on the east side of the test room. Most walls are inside a warehouse. However, one wall of the test room and two walls of the conference room are outside walls.

The EC is attached to the west side of the test room and is separated from it by a curtain wall with double glazed clear glass window. The purpose of this chamber is to allow simulation of a wide range of outdoor temperatures. The EC also contains an array of lamps that simulate solar radiation to investigate the impact of solar radiation under summer cooling conditions.

The test facility is supported by a 150-channel data acquisition system that measures a large number of temperatures as well as airflow and underfloor pressure in sufficient details to allow detailed calculation of the heat balance of the chamber. The project team developed a data processing system to reduce the results of all experiments, which are summarized in Appendix A.

Occupied Space/Test Room

As shown in Figure 2, the test room is a 7.9-meter (m) (26-foot [ft]) square with an area of 63 meters squared (m^2) (676 feet squared [ft^2]) and a height of 2.7 m (9 ft) where all room air stratification experiments were conducted. Temperature sensors, thermal manikins, personal computers, desk lamps, and other equipment were placed in this room to simulate typical office arrangements. Interior spaces were simulated by placing foam insulating panels on the west window wall and over the windows on the south conference room wall. The west panels were removed when perimeter spaces were simulated.

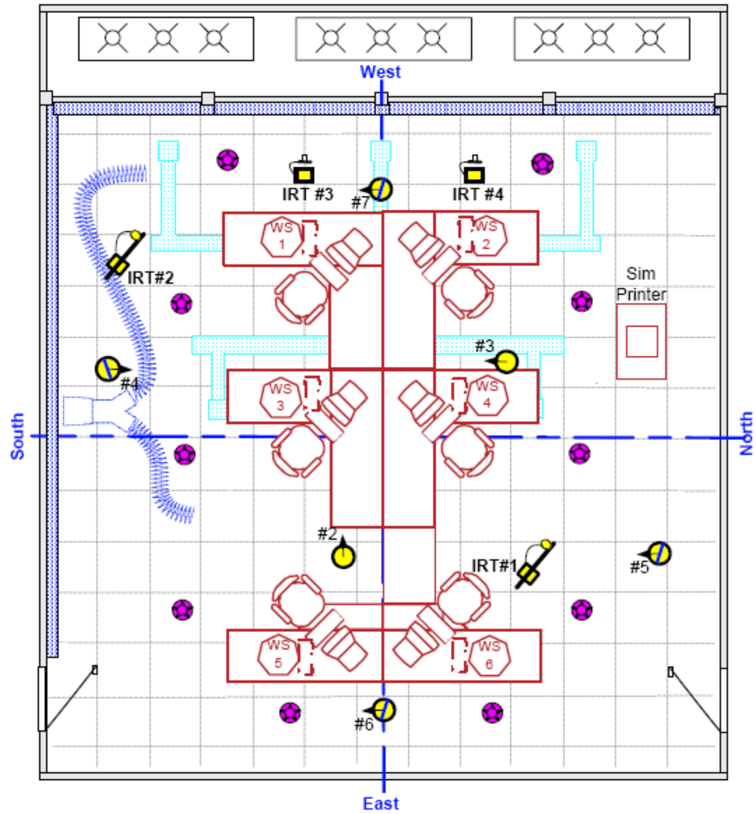

Figure 2. Test chamber layout

3.1.2. Findings Based on Interior Zone Tests

Diffuser Type

The project team investigated the performance of three diffuser types (four including perimeter zones) with distinctly different characteristics that provide a good representation of the range of characteristics expected in practice. Figure 3 shows a comparison between typical stratification profiles for these diffusers.

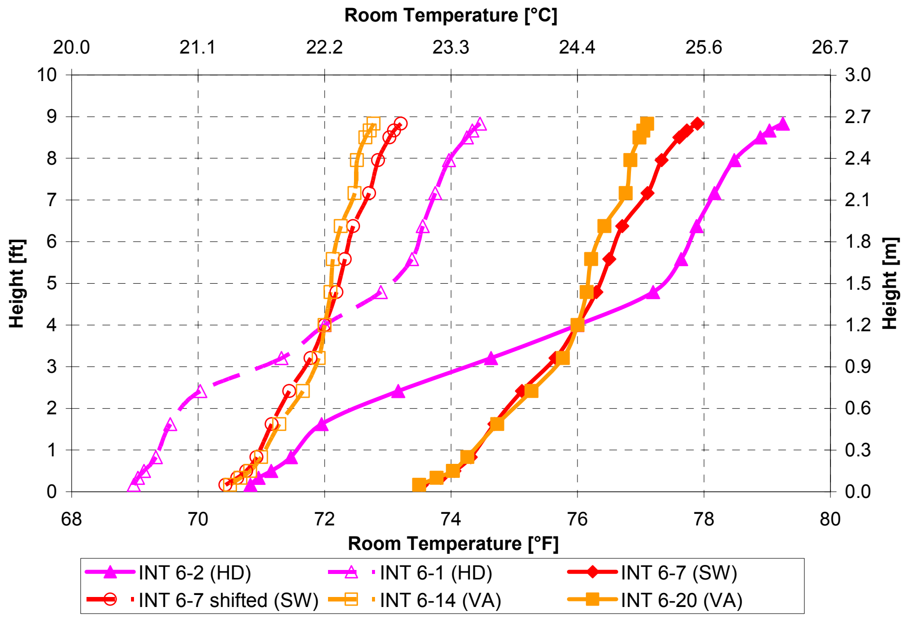

Figure 3. Comparison of standard swirl, horizontal discharge, and variable area diffusers under peak design conditions

To summarize briefly:

- Swirl diffusers come in two varieties.
  - ‘Standard’ designs, which are the most prevalent; are passive (not physically controlled, although variants are actively controlled in some manner); and have discharge patterns that impart a swirl motion to the vertically discharged airflow.
  - Low throw or, as referred to in this report, horizontal discharge (HD) swirls, which impart a swirl in a horizontal, rather than vertical, discharge pattern.
- Variable area diffusers (VA) represented best by York’s MIT diffusers, for which the outlet area is modulated by a moving damper.[1]

Overall conclusions relative to diffuser type follow:

- Standard swirl diffusers can produce large differences in stratification depending on design and operating conditions. HD swirls and VA diffusers, on the other hand, show a relatively narrow range of stratification performance. In other words, variation in throw drives the performance of standard swirl, but not HD and VA, diffusers. VA diffusers

[1] The testing reported here used York’s original design, which has been largely replaced by the newer MIT 2. In this device, the moving damper is replaced by a time-modulated damper and fixed outlet area. Due to this and other design changes, the performance of the MIT 2 may differ from the results shown here.

produce a very consistent profile over a broad range of design and operating conditions. HD swirls are also likely to produce a consistent profile over a broad range of conditions. However, this expectation could not be confirmed because HD swirls were tested on a limited range of conditions. See Table 1 for a summary of characteristics for the diffusers tested.

- At typical diffuser design conditions, both standard swirl and VA diffusers produce the same profile shape and stratification for a given load and thermostat setting.
- Airflow requirements are nominally the same for standard swirl and VA diffusers, regardless of the degree of stratification for the same load condition. However, when comfort effects are factored in and compared at equivalent average occupied zone temperatures, swirl diffusers will operate with less airflow in proportion to the amount of stratification created, which depends on the number of diffusers used. Equivalent comfort can be realized by increasing the number of swirl diffusers so that they operate below their design airflow and then increasing the setpoint relative to the VA setpoint.

Table 1: Diffuser characteristics summary

	Discharge area	**Vertical throw**	**Nominal design airflow, (cfm)**
Standard swirl	Constant	Variable	80
HD swirl	Constant	Nearly constant	60
Variable area	Variable	Constant	150
Linear	Constant	Variable	250 (48")

Diffusers Tests

Design Conditions

As pointed out above, swirl diffusers have a greater potential for managing stratification because of the variation of throw with operating conditions. Test results presented in Figure 4 show the extent that changing the number of diffusers can change the stratification in the occupied zone under the same load conditions and setpoint.

Other results indicate that swirl diffusers produce the same profile independent of load conditions when the throw height is the same. This result is useful for design but not for operations, because the throw varies as load changes in variable air volume (VAV) systems. For constant-volume systems, the profile would stay the same with load (at its design condition), only the supply air temperature (SAT) varies to maintain the thermostat setpoint (Webster et al. 2002b). When the throw height is changed (by increasing diffusers or changing airflow, for example, changing the load or setpoint) for the same number of diffusers, changes in the stratification appear.

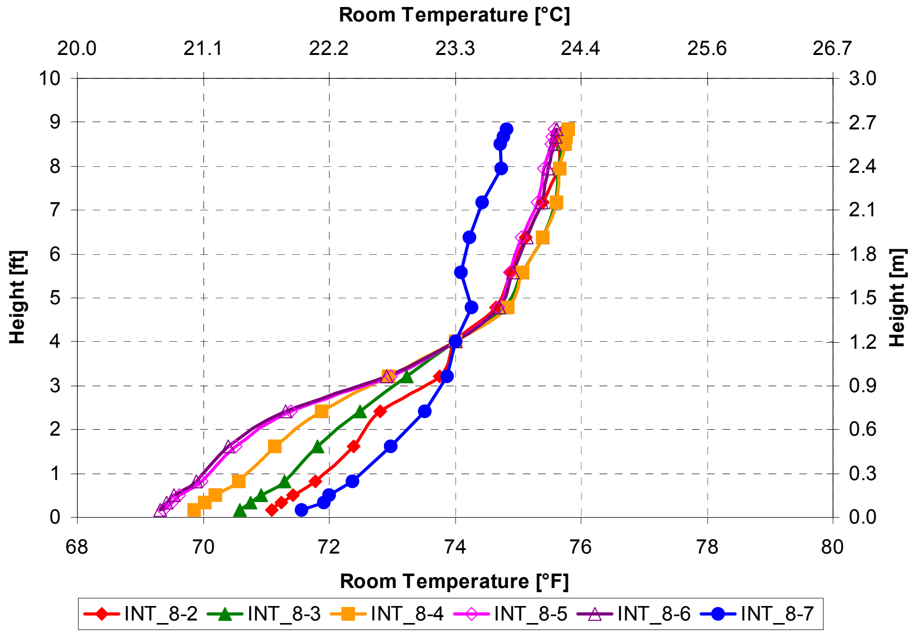

Figure 4. Results of diffuser throw height study for standard swirl diffusers

These results, combined with the preliminary analysis comparing airflow requirements based on equivalent comfort conditions, suggest that swirl diffusers offer designers the flexibility to optimize stratification (reduce airflow while maintaining comfort) in a way that VA and HD swirl diffusers do not. For HD swirls, despite the fact that stratification is somewhat fixed, the stratification is maximized, which results in minimizing the airflow. However, in some cases this can result in occupied-zone temperature differences that exceed the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55 criteria.

Operating Conditions, Load Variation

The results (shown in Figure 5) obtained by the load variation study are somewhat mixed, and further research is needed to corroborate the researchers' overall impression that the profile shape does not change as load is varied. If true, it result will have very interesting and important implications on practice: It would mean that during design practitioners could "dial in" the stratification level they feel is appropriate and expect that it would remain consistent during load variations, producing a reliable comfort environment. It also would allow optimization of stratification during commissioning at reduced loads, thereby saving cost and effort.

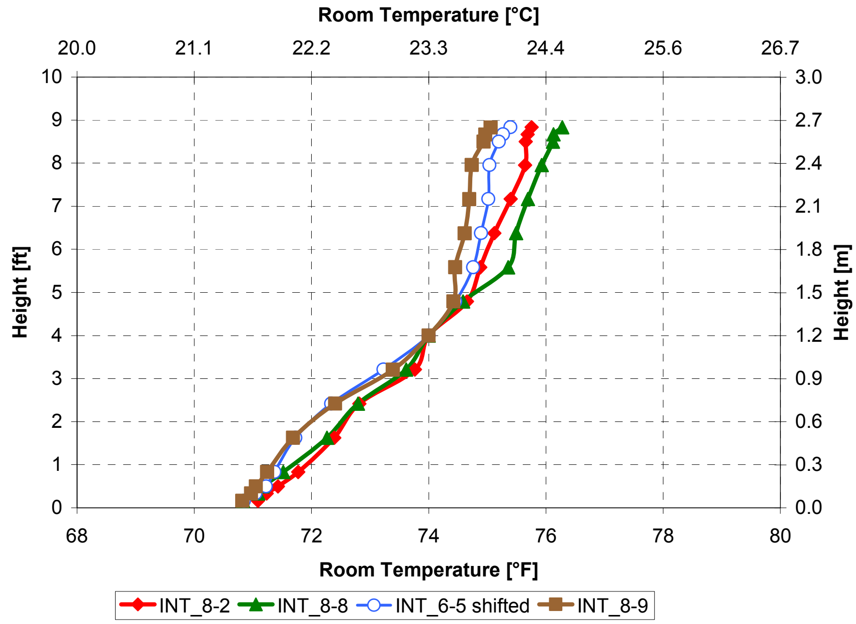

Figure 5. Results of load variation study for standard swirl diffusers

Floor Leakage Impacts on Swirl and VA Diffusers

This testing produced important results that should prove helpful to design, commissioning, and operations. For this, the team defined different leakage categories:

- Category 1 leakage: air leaving the system, which represents airflow loss
- Category 2 leakage: air enters the conditioned space

The primary impact of floor leakage occurs with Category 2 leakage.

The team generally used leakage rates greater than would be expected in real systems (ranging from 0.12 to 0.3 cfm/ft^2 over all the leakage tests). However, the ranges were not outside of the realm of possibility based on reports received from commissioning studies on real buildings.

The effect of floor leakage on stratification appears to be different for swirl vs. VA diffusers, as shown in Figure 6. For pressure modulated swirl systems, stratification is increased due to two effects:

- The leakage itself, which created a displacement-like component in the airflow
- A reduction in airflow through the diffusers, which decreases diffuser throw

Additional findings for swirl diffusers follow:

- Leakage is proportional to the airflow reduction, such that the ratio to total room airflow is constant.
- As the plenum pressure is reduced the amount of Category 1 leakage is reduced.

For VA systems using constant pressure plenums, a similar increase in stratification was observed. However, in this case the effect appears to be due to leakage alone, since the diffusers are insensitive to airflow changes because they modulate. However, because the pressure is constant, the relative proportion of leakage airflow increases as load decreases. This increase can lead to a loss of control at low load conditions.

Designers typically consider all leakage as undesirable. However, these results suggest that such concern may be misplaced. Floor leakage may not be particularity deleterious in pressure-controlled swirl systems if it increases stratification, reduces Category 1 leakage, and does not create local comfort problems. This finding is also somewhat true for constant-pressure VA systems, except that as the system is throttled, the percentage of leakage gets greater, potentially leading to loss of control at low loads and no reduction in Category 1 leakage.

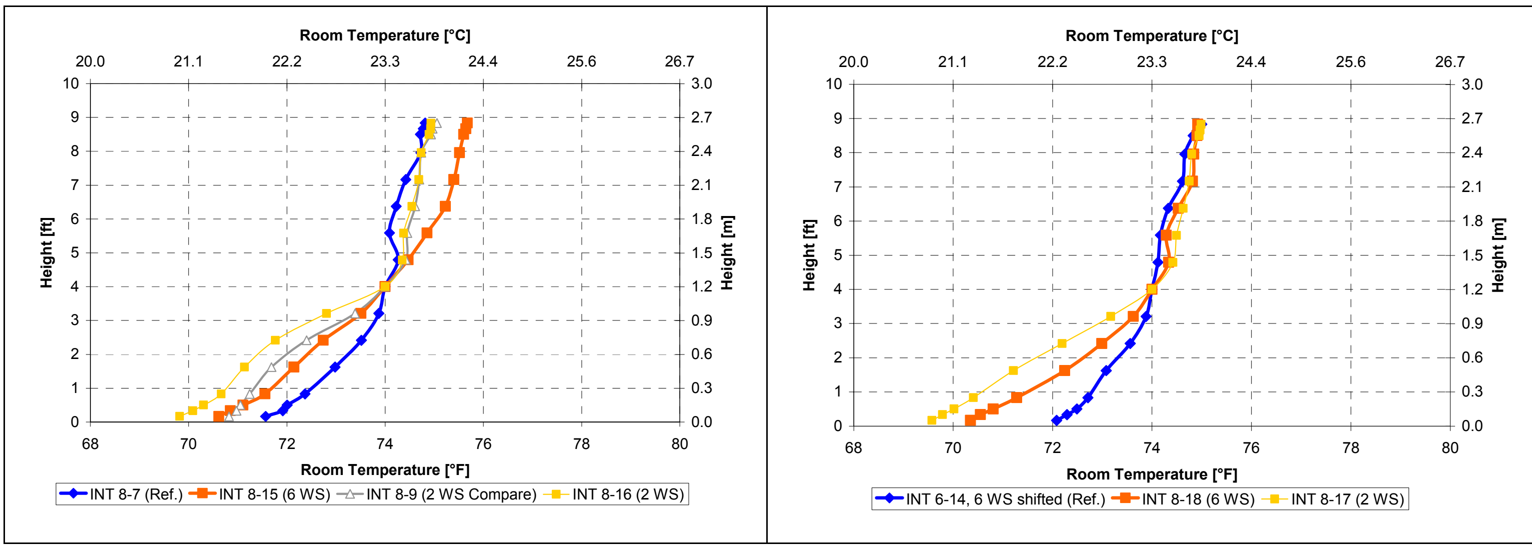

Figure 6. Results of leakage study for swirl (left) and VA diffusers under high and low load conditions

3.1.3. Findings from Perimeter Zone Testing

For perimeter testing, results fall into three categories of studies:

- The effect on stratification performance of diffuser throw
- Diffuser type
- The impact of blinds closed vs. blinds open

Results are discussed below.

Diffuser Throw

Perimeter loads derived from peak solar gain can be larger than interior loads by a factor of two, and the type of thermal plume is different than for internal loads. However, the perimeter load stratification performance appears to be dominated by diffuser characteristics, much as it is for interior zones. To study this impact, the team tested linear bar grilles, the predominate type of perimeter diffuser used today in most UFAD buildings (except of coarse, those with the York MIT system). In peak solar tests (which involve two banks of simulator lights), the team decreased the throw characteristics by both increasing the number of diffusers and decreasing the (sideways from horizontal) angle of discharge of internal “flow-spreading” vanes. Although the team was unable to conduct enough tests to definitively determine the effect of vanes, results clearly show that stratification is increased and airflow is reduced as throw is reduced (See Figure 7). For example, airflow required for a load condition of about 10 watts (W)/ft[2] and 10 diffusers with 53° discharge, versus 8 diffusers with vertical (90°) discharge is reduced by about 23%.

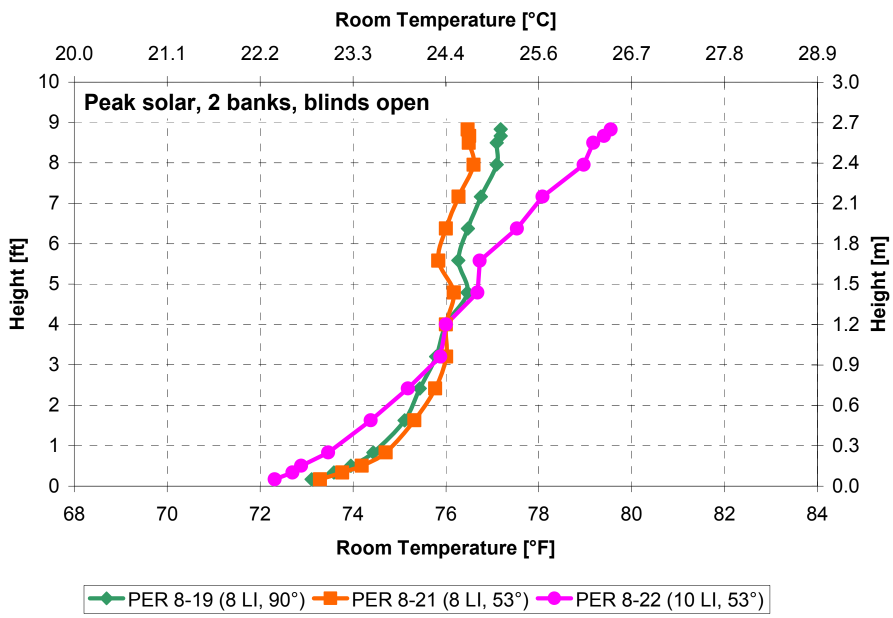

Figure 7. Linear bar grille performance comparing throw heights

Diffuser Type

To compare the performance of different diffuser types, researchers included the known diffuser types of VA and linear bar grille and added a test using swirl diffusers located only in the interior so there were no diffusers at the window. This last case represents the ultimate possibility for reducing the interaction between the diffuser flow and the window thermal plume.

Results from these tests (shown in Figure 8) indicate that linear bar grilles and VA diffusers performed comparably. However, researcher observed a large increase in stratification for the case with no window diffusers. In fact, so the increase was so high that it exceeded the ASHRAE Standard 55 recommended limits. The project team estimates that this larger stratification results in a nominal 12% lower airflow requirement under the conditions tested.

This configuration deserves more study, since optimizing the competing elements of occupied zone difference and average temperature (i.e., equivalent comfort) would likely alter the conclusions from this single test. For example, to increase the occupied zone temperature, the setpoint could be increased thus lowering the airflow, but the number of diffusers would have to be increased to reduce the stratification which may increase the airflow requirements.

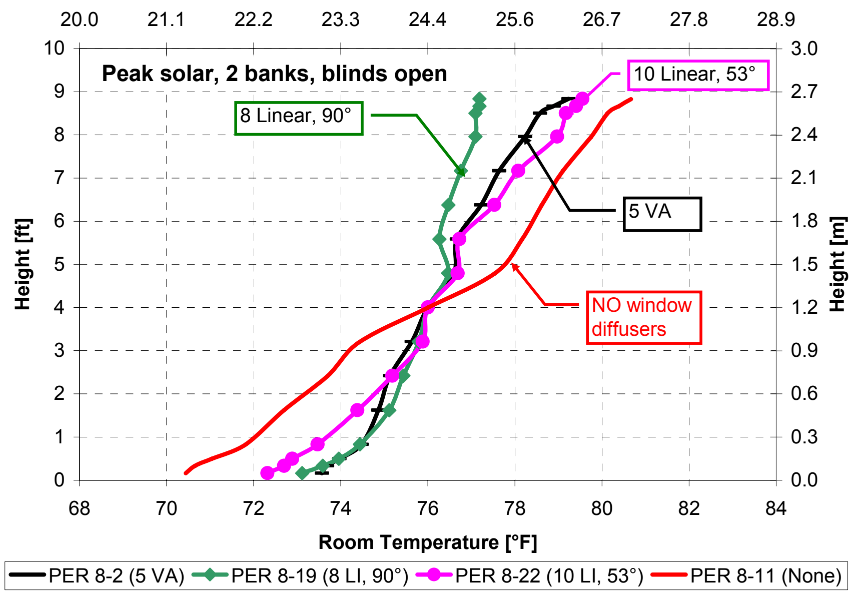

Figure 8. Diffuser type comparison for perimeter zones

Impact of Blinds

Lowering blinds is a common practice in real buildings, especially under peak load conditions when direct solar gain and glare become intolerable. Tests conducted for the peak solar conditions revealed that lowering the blinds dramatically increases the stratification even though the total gain is reduced, as shown in Figure 9. Under peak solar conditions, lowering the blinds showed the following impacts:

- Total heat gain (solar plus internal loads) decreased by about 15%
- Room temperature difference increased by almost 50% (less heat transferred to the plenum)
- Occupied-zone temperature remained virtually unchanged
- Estimated airflow (on equal heat gain basis) decreased by about 25%

These results indicate that lowered blinds has a substantial impact on the performance of perimeter zones. This impact should be studied in more detail to develop a better understanding of its implications on design and energy performance and its demand response possibilities.

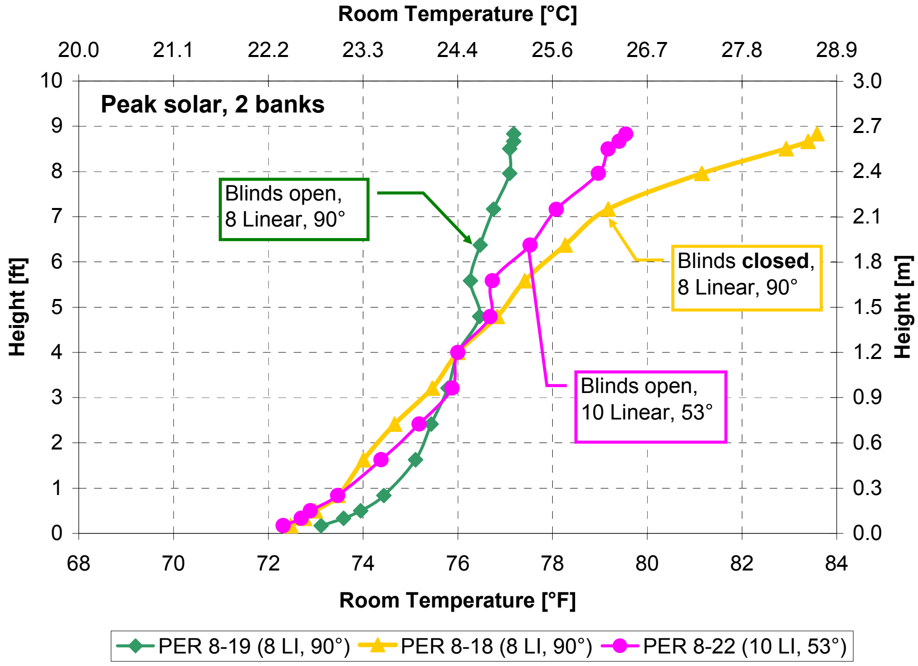

Figure 9. Linear bar grille performance with and without blinds

3.2. Salt Water Tank Testing and RAS Model Development

3.2.1. Introduction

The objective of the salt water experiments and RAS model development is to generate algorithms for the interface height and temperatures of the occupied zone and the upper zone for implementation in a UFAD module in EnergyPlus. This approach is predicated on the idea representation of the stratification in the space generated by the UFAD flow is needed to provide accurate estimates of heat transfer and comfort calculation. Further, this representation must be sufficiently simple to enable incorporation into EnergyPlus without adding significantly to the computational overhead.

The simplest representation of stratification that captures difference in temperatures between the floor and the ceiling is to divide the space into two zones—a lower occupied zone and an upper zone—and characterize each by a single temperature. The transition height between the two zones is an unknown and depends on the parameters of the UFAD system. It is recognized that this representation oversimplifies the real stratification produced by a real UFAD system. In practice, the zones are not uniform in temperature and the transition height is often difficult to define from measured temperature profiles. However, a two-zone representation captures the first-order effects of the stratification in a way that is simple enough for implementation within EnergyPlus.

Zonal models of this type exist in the literature, but all arbitrarily assign the location of the zones. Thus the modeler must allocate zones arbitrarily. In contrast, this project developed a model of the flow that allows calculation of the heights of the zones and their temperatures based on the input parameters of the system. The model is based on a physical description of the flow as determined from laboratory experiments. These laboratory experiments and the model are, in turn, compared with full-scale measurements.

Thus the model and, consequently, the implementation in EnergyPlus are based on a description of the physics as they are currently understood. Because the approximations and assumptions behind this description of the physics are clearly stated, it is possible to develop a rational methodology—based on improving these approximations and extending the ranges of validity of the assumptions—for enhancing the model.

The basic assumption is that the internal gains within the space are from discrete sources that produce turbulent plumes. These plumes are either point-source for isolated heat sources, such as people or equipment, or area-sources caused by solar radiation at a window, for example. The heat generated by these sources rises in the plumes to the upper zone of the space. The UFAD system delivers cool air through diffusers located in the raised floor in the form of an upward-directed turbulent flow. Since this cool air is dense compared with the air in the space it rises a finite height and then reverses direction and falls back towards the floor. As it falls, the diffuser flow also brings warm air down from the upper part of the space.

The height that the diffuser flow reaches is called the diffuser throw, and this height can be varied by increasing the flow through the diffuser (by increasing the plenum pressure). The stratification within the room is determined by this combination of the diffuser flow and the plumes. In a given space these are, in turn, determined by the type and number of diffusers (represented by n), the number of the plumes (represented by m) and bulk properties, such as the ventilation flow rate and the total heat load.

Depending on whether the number of diffusers exceeds the number of plumes or vice-versa, the team uses either a multi-diffuser ($n > m$) or a multi-plume ($n < m$) approach. For example, for the multi-diffuser case, the space is divided into sub-spaces, each containing a single plume and n/m diffusers. Thus the problem reduces to developing models for a single plume with a number of diffusers or a single diffuser with several plumes. These can, in turn, both be related to the basic model derived for a single plume and a single diffuser. This approach is shown schematically in Figure 10 and applies to the interior zone with point sources and the exterior zone with area sources. It is also possible to include additional effects—such as the effects of elevated sources and leakage from the plenum into the space—as submodels.

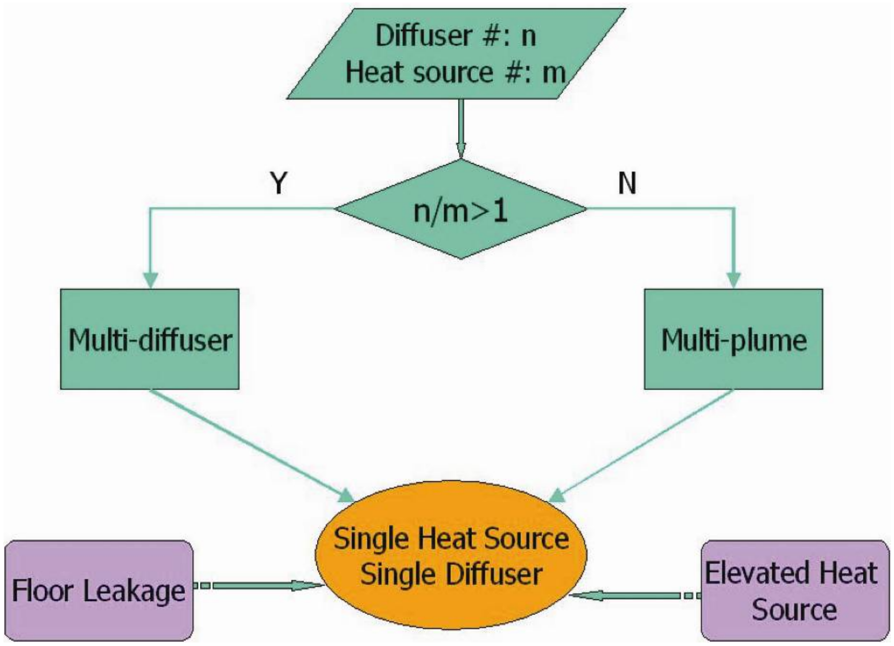

Figure 10. Modeling process schematic

This project studied the multi-diffuser and multi-plume cases separately in specific laboratory experiments and developed models for the resulting stratification. These interior zone experiments are compared with full-scale tests in Appenidix C. Based on these comparisons, scaling laws for the stratification were determined and implemented in EnergyPlus.

3.2.2. Laboratory Experiments and Theoretical Model

The experiments were carried out in a water tank. Plumes of dense salt water were used to represent heat sources and jets of fresh water were used to simulate the diffuser flows. As a result, the model is inverted with respect to reality and the return is placed at the base of the tank. In the discussion of the results, the usual room orientation is used. (See Appendix C for completed details of the methodology.)

Measurements of the stratification were made by both using digital image processing and removing samples for analysis. Results provided the basic data for comparison with the theoretical models.

The theoretical model is based on representing the flow in a plume using standard plume equations for conservation of mass, momentum, and buoyancy. Turbulence in the plume causes surrounding air to be entrained into the plume and carried upwards. This entrainment and the increase in volume flux in the plume with height are represented by an entrainment constant. Similarly, the flow from the diffuser is represented as a negatively buoyant jet, and again entrainment into the jet is characterized using a (different) entrainment constant.

When the diffuser flow impinges on the upper warm zone it mixes with the warm air and then brings this warm air down as it reverses direction. This penetrative entrainment is characterized by an entrainment rate E, which is a function of the stability of the stratification. Comparison of the model and experiments was used to determine E.

The model is then based on the assumption that the stratification consists of two layers each of uniform temperature separated by a sharp interface. Volume conservation and a heat balance are applied to each layer, and the resulting equations are solved numerically. The predicted profiles were compared with those measured in the experiments.

3.2.3. Interior Zone Modeling

Multi-Diffuser Model

In the case where the number of diffusers n exceeds the number of plumes m, the space is divided into zones each with one plume and n/m diffusers. Figure 11 shows false color images of the stratification for a single plume and two diffusers and also for an elevated plume. The warm upper zone is clearly visible, and elevating the heat source makes this zone warmer. A comparison of the measured profiles and the model results is shown on Figure 12. These results indicate that the model is in agreement with the measured profiles and that both the model and the measured profiles exhibit the same trends. The trend in this case involves maintaining same heat load and ventilation rate, which is equivalent to reducing the plenum pressure as the number of diffusers is increased. Increasing the number of diffusers lowers the height of the lower zone and decreases its temperature. The return temperature remains unchanged.

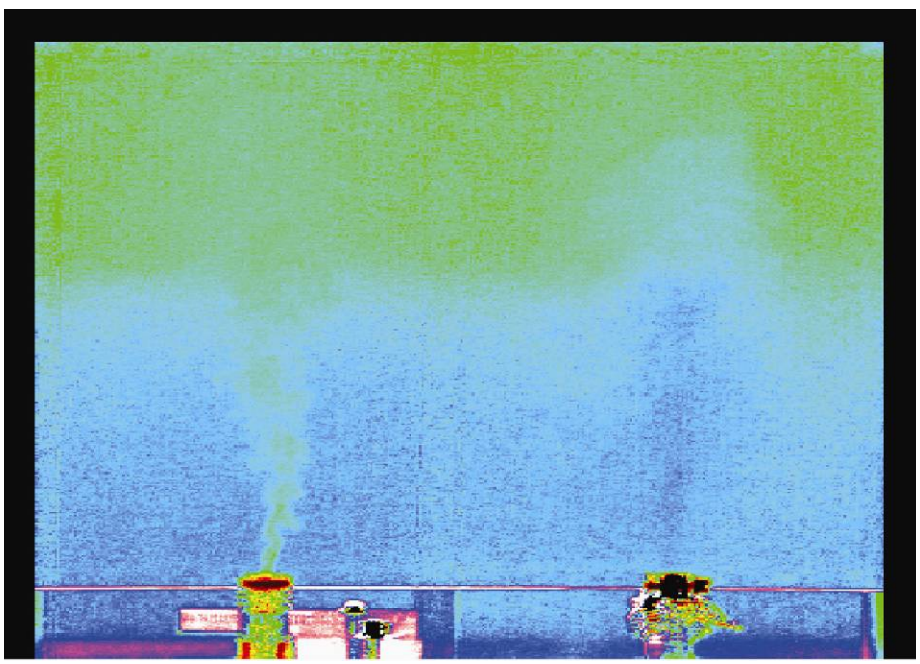

Figure 11. Photo image of stratification layers

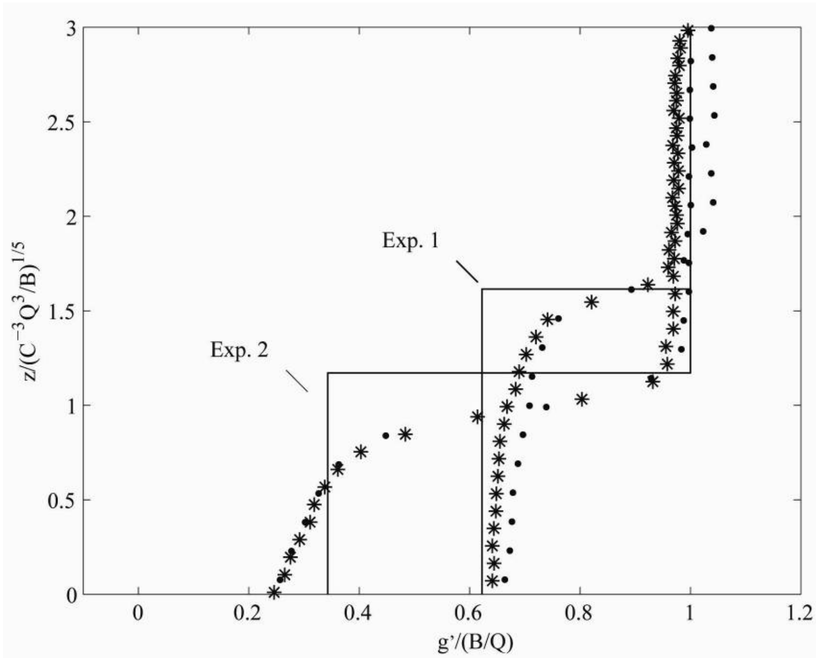

Figure 12. Comparison of salt tank and modeling results

On the other hand, if the plenum pressure is maintained while the number of open diffusers is increased, the ventilation rate increases. In this case, the lower zone increases in height, and the return temperature decreases. Again good agreement is found between the model and the experiments (Figure 13).

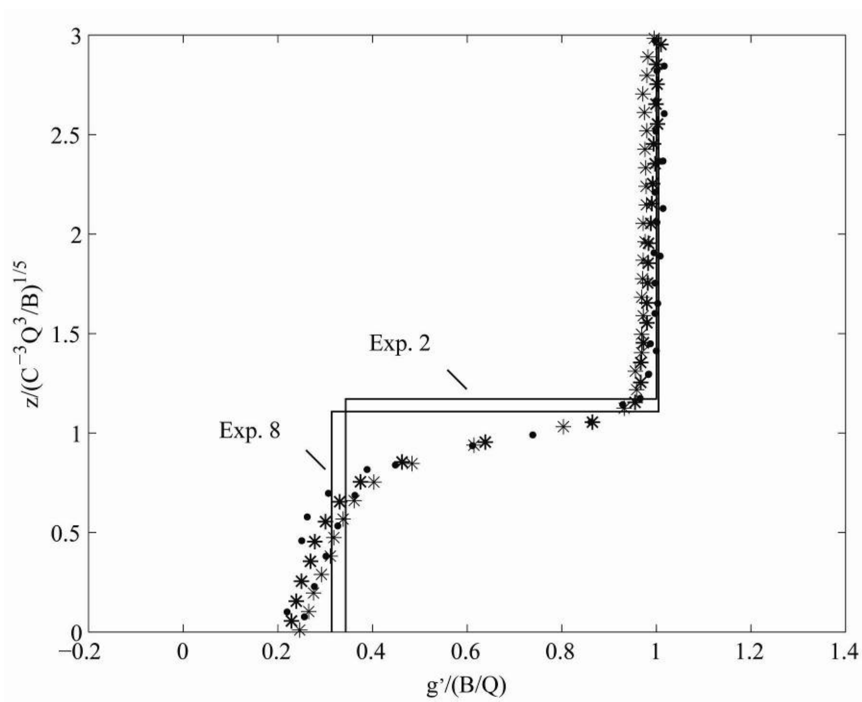

Figure 13. Multi-diffuser model results

Multi-Plume Model

When the number of diffusers n is less than the number of plumes, the space is divided into n zones each with m/n plumes. This situation is more complicated than the multi-diffuser flow, since in contrast to that case, the plumes do not necessarily have the same strength.

When the plumes are of equal strength, a two-zone stratification is expected, and the theoretical model is easily adapted for that case. Figure 14 shows the comparison between the model and the experimental measurements. The two-zone stratification is observed and well predicted by the model.

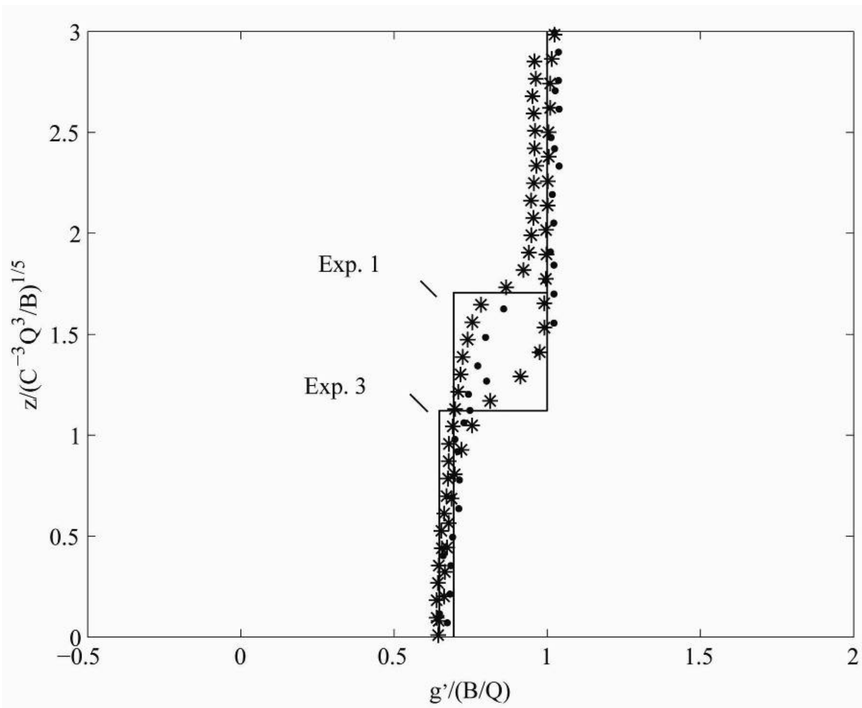

Figure 14. Multi-plume comparison of experimental and modeling results

In the case where the plumes have different strengths the situation becomes much more complicated. For example, for two unequal plumes, a three layer stratification is expected, as the weaker plume will not have sufficient buoyancy to reach the ceiling. Further, it is no longer clear that the diffuser flow will penetrate to the upper zone or where the warm air entrained from that layer will be distributed. As a result, the model is much more complicated and has a number of other unknowns that make it difficult to compare with the experiments.

One result from the model is that the middle zone is likely either to be thin or to have a small temperature difference from the upper zone. The project team conducted extensive experiments but never observed this middle layer. Nonetheless, the model gives reasonable comparisons with the experiments (Figure 15).

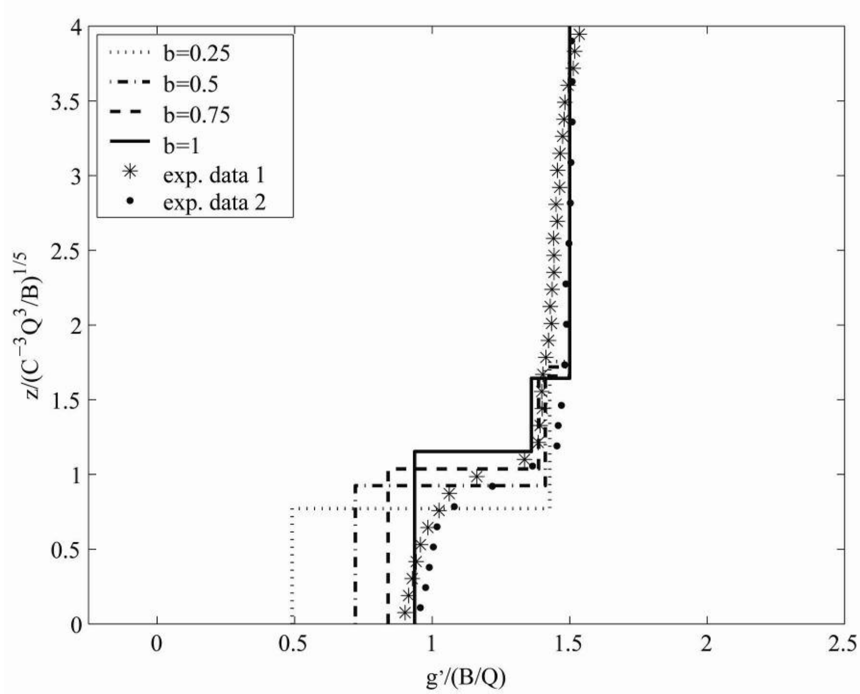

Figure 15. Unequal strength plumes experimental and modeling results

Plumes of unequal strength remain a concern in the analysis and lead to significant uncertainty in the implementation in EnergyPlus. This uncertainty manifests itself in the apportionment of the gains to the occupied and upper zones. Further research is needed to address this important issue.

3.2.4. Perimeter Zone

The exterior zone differs from the interior in that the plume is an area plume, which results from heating the façade. In these experiments, the area plume was represented using a line plume extending across the width of the tank. Figure 16 shows a shadowgraph image of the flow with the wall plume generated by the line source. The theoretical model was modified by using plume equations for a line plume, which primarily increases the volume flux in the plume with height.

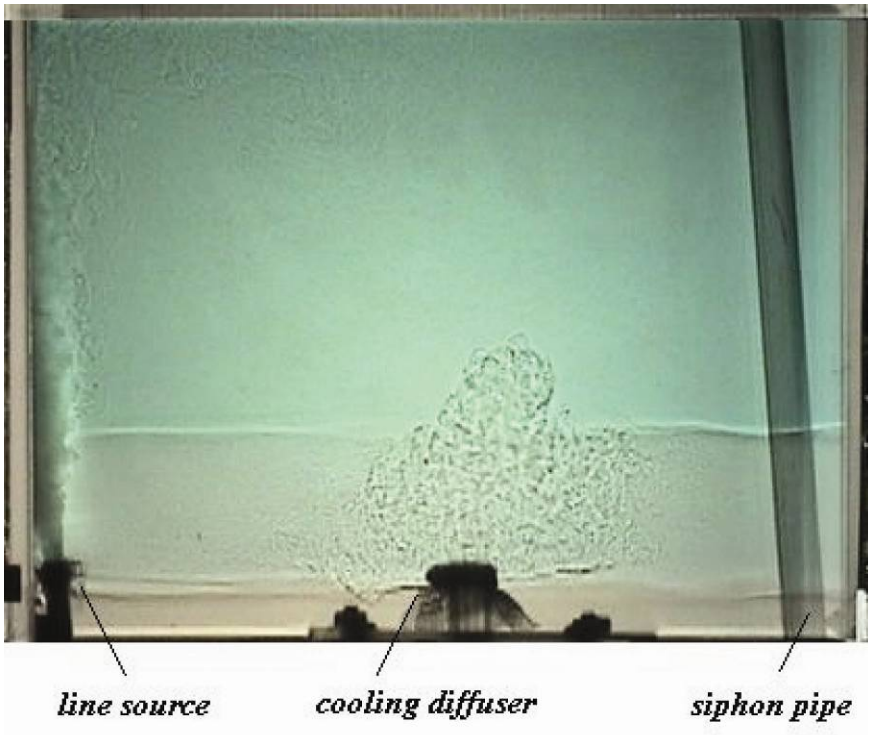

Figure 16. Shadow graph showing perimeter zone (line plume) experiment

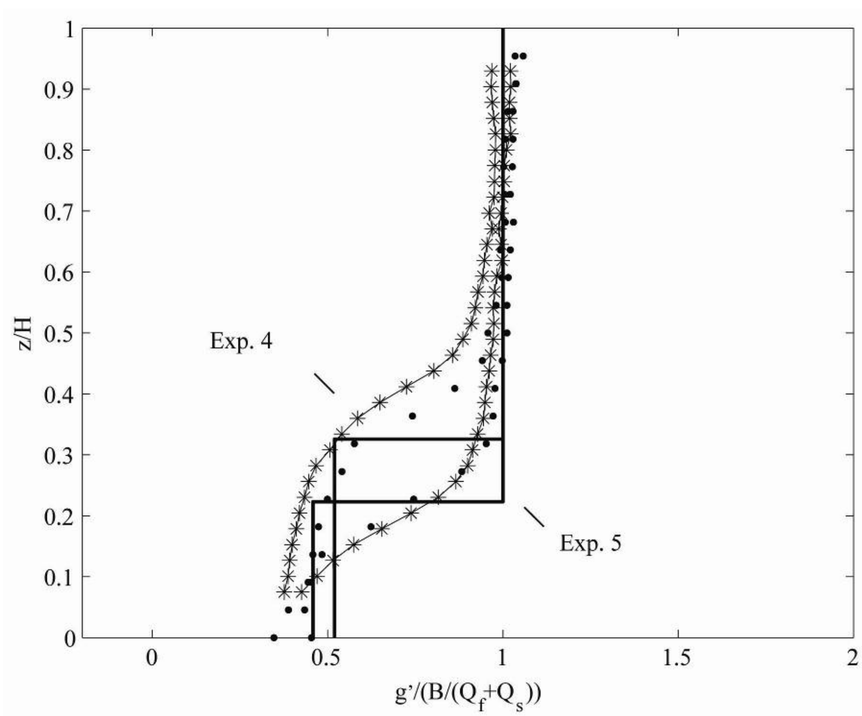

Figure 17. Perimeter zone modeling and experimental results comparison

Figure 17 shows the comparison between the new model and the line plume experiments. The agreement is not as good as for a point-source plume, mainly due to uncertainties in the entrainment rate for the line plume. Nevertheless, the model captures the main behavior.

3.2.5. Comparison with Full-Scale Tests and Implementation in EnergyPlus

The experiments and the agreement with the theoretical models provided confidence that the basic physics of the UFAD flows have been captured. Two further steps remained in providing a valid implementation in EnergyPlus. The first step was to show that agreement between the laboratory experiments and the full-scale tests. This was shown qualitatively by comparing smoke visualizations in the room and dye tests in the laboratory. As Figure 18 illustrates, the same flow regimes were observed. Quantitatively, the team checked that the model, using the full-scale test parameters, reproduces the measured temperature profiles. This is confirmed in Figure 19.

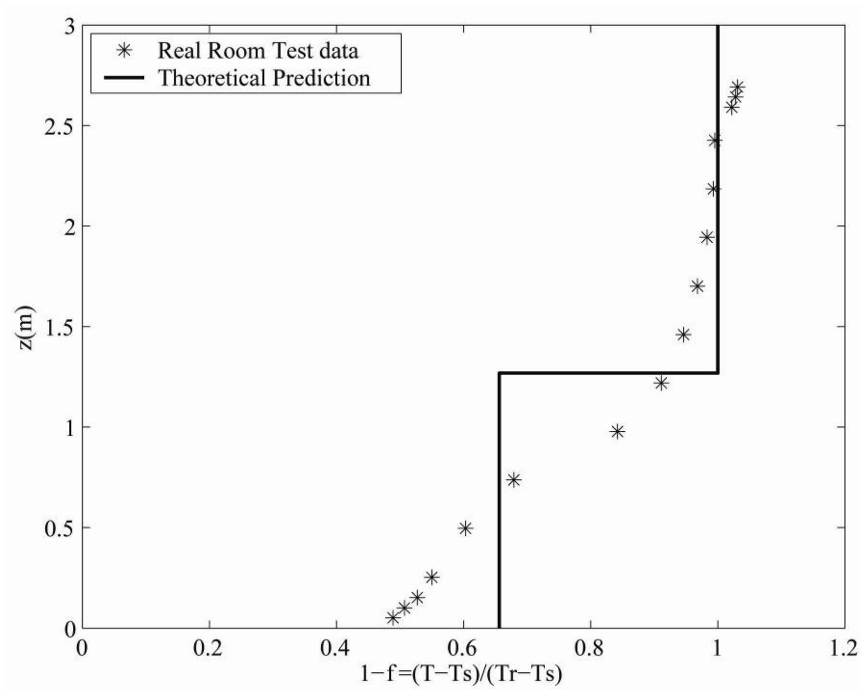

Figure 18. Comparison of modeling and full scale results

Figure 19. Full scale testing results

The second step is to provide algorithms for the temperature stratification and the occupied zone depths in terms of the external parameters—the ventilation flow rate, the total heat load, the number and area of the diffusers, and the number of plumes. Previous work by the team confirms that these are the parameters that govern the physics of the flow. For example, the team's work has shown that the room height is not a governing parameter for the steady-state stratification. Figure 20 shows the results in non-dimensional form for stratification strength and the occupied zone stratification height for the interior zone experiments. These data include both laboratory and the test room data. The fact that these data collapse onto single lines shows that the team has captured the physics correctly and that the laboratory results scale up to full scale.

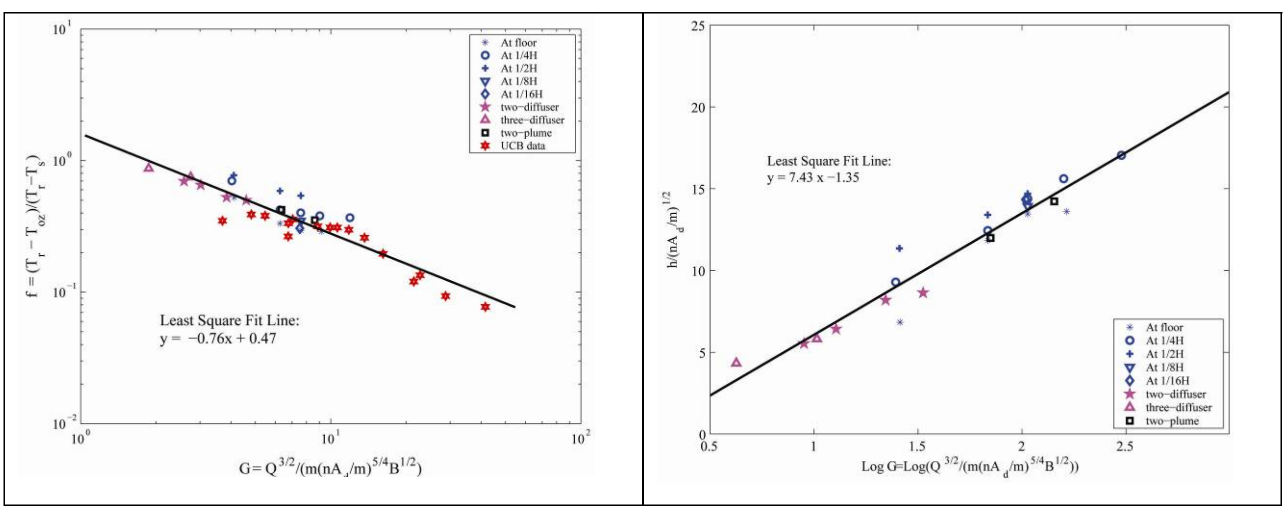

Figure 20. Experimental results for interior zones

Figure 21 shows similar results of bench-scale experiments for the perimeter zone.

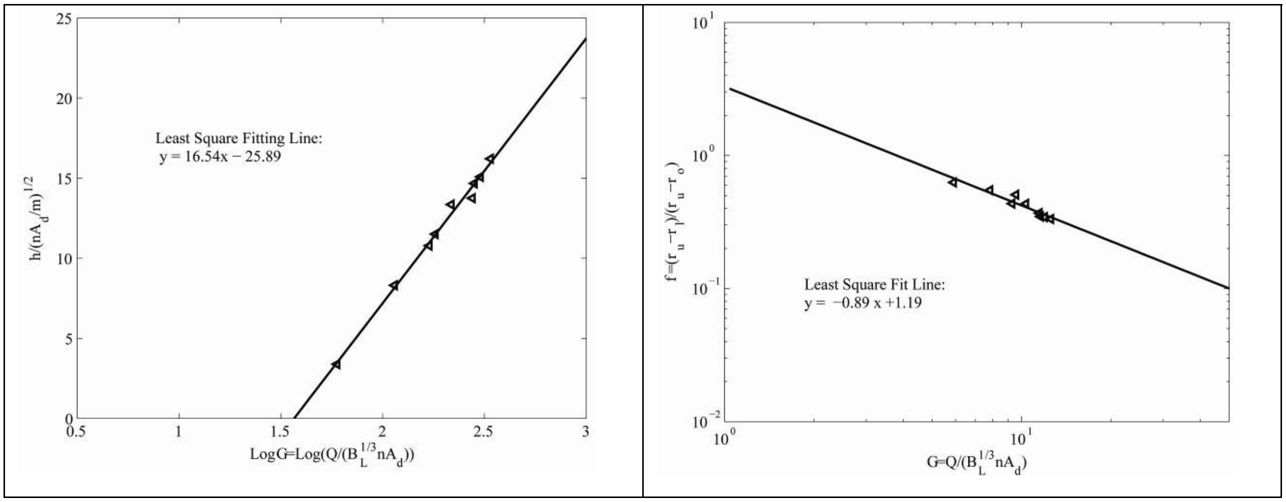

Figure 21. Experimental results for perimeter zones showing regression line fitted to salt tank experimental results

These results helped to inform the development of algorithms used in EnergyPlus.

3.3. Underfloor Plenum Testing and Modeling

This section summarizes the work performed in support of Task 2.3 (Underfloor Plenum Testing) and Task 2.5 (Underfloor Plenum Model Development). The ultimate goal of these tasks was to develop a model capable of calculating the thermal performance of underfloor air supply plenums and suitable for implementation in EnergyPlus. A secondary goal was to conduct fundamental research that provides a sound theoretical and practical understanding of underfloor plenum energy performance in terms of heat transfer entering the plenum and the resulting airflow and temperature distributions.

The work is summarized in three sections below. Section 4.1 describes full-scale experiments in CBE's underfloor plenum test facility development of a computational fluid dynamics (CFD) model of underfloor plenums validation of the CFD plenum model by comparison with the full-scale experimental database. Section 3.3.1 describes use of the validated CFD plenum model to conduct simulations of a broader range of plenum design and operational parameters development of a simplified underfloor plenum model based on the CFD database for implementation into EnergyPlus.

Preliminary validation of the underfloor plenum model in EnergyPlus is described in Section 4.4.3.3. In Section 4.3.3, provides a summary of the results of the simplified heat balance modeling study of heat transfer pathways in UFAD systems. Full details of all the work on underfloor plenum testing and modeling are presented in Part IV of this final report, as well as in attached publications (Jin et al. 2005, 2006; Bauman et al. 2006).

3.3.1. Testing and CFD Modeling of Underfloor Air Supply Plenums

This section describes the development and validation of a CFD model for predicting the airflow and thermal performance of underfloor air supply plenums. To provide validation data for comparison with the CFD model, a series of experiments in a full-scale underfloor plenum test facility were carried out.

Full-Scale Underfloor Plenum Test Facility

The underfloor air supply plenum test facility was installed in December 2000 in a university warehouse building with an exposed concrete slab floor (see Figure 22). The plenum is 6.7 m (22 ft) by 22.6 m (74 ft) and 0.305-m (1-ft) high. The raised floor system was constructed from commercially available floor panels and included 16 VAV floor diffusers. An HVAC system delivers supply air at a controlled temperature and volume into the underfloor plenum. The HVAC system has 2,330 cfm (1100 liters per second [L/s]) as the maximum supply airflow and 13–32°C (55–90°F) as the operable temperature control. The plenum inlet was installed at the middle of the side wall next to the HVAC system.

Figure 22. Photo of underfloor air supply plenum test facility

Preliminary calculations showed that the inlet configuration can have a significant impact on the plenum air temperature variation and heat gain. Two different inlet configurations were installed and tested to provide validation data for the CFD model:

- Single focused jet, representative of the most basic plenum inlet design
- Two jets, which is a simplified version of an inlet vane configuration that produces multiple jets to spread out the incoming air

To record the boundary and test conditions for each of the two inlet configurations, a data acquisition system with associated sensors (at multiple locations) was installed in the test facility. The following test conditions were measured:

- Inlet temperature, velocity, and direction

- Plenum air temperature and velocity
- Slab surface temperature, heat flux, and temperature to a depth of 4"
- Surface temperature of underside of floor panels
- Room air temperature
- Room ceiling surface temperature

For comparison with the CFD plenum model, the team conducted two steady-state experiments, one for each inlet configuration. In the experiments, the team delivered a constant temperature and volume of air for at least 72 hours before taking measurements. All of the transient behaviors were minimized after such a relatively long time. Data showed that the variation of temperature and heat flux was negligible during the short period of time (typically 15 minutes) used for the data collection period.

CFD Plenum Model

CFD programs provide a detailed analysis of the thermal fluid phenomena, producing simulation results that include qualitative values—such as airflow pattern—and quantitative values—such as air velocity, temperature, turbulence kinetic energy, Reynolds stress, and surface heat flux. The parameters reported by the CFD code can be compared with the experimental data. A commercially available CFD computer program was used to develop an exact model of the full-scale plenum test facility. The CFD code solves the unsteady Navier-Stokes equations in their conservation form and also includes a standard k-ε turbulence model. Full details of the CFD plenum model are presented in Appendix D and elsewhere (Jin et al. 2006).

Comparison of CFD Model Predictions with Experimental Data

Generally, the comparison of CFD results with the experimental data is the most important part of the reporting process for an indoor environment CFD analysis. The quantitative comparison between CFD predictions and experimental data included the following:

- Temperature at each diffuser.
- Air velocity and slab heat flux at selected locations in the plenum. The plenum heat gain was calculated based on the measured inlet/outlet temperature difference (where the outlet temperature represents the average of all measured diffuser temperatures) in combination with the airflow volume in the experiment. It can also be computed from CFD results using the same approach.
- Heat transfer into the plenum from above the floor and under the slab. These measurements were obtained from the CFD results. It was compared against the heat gain of the plenum using temperature and air volume approach (above) to check the convergence of the CFD calculations.

As an example, Figure 23 presents one comparison of the CFD model predictions to measured data. The figure shows a contour plot of the predicted temperature distribution at mid-height of the plenum for the focused jet inlet configuration. Each number in the contour plot represents the average air temperature over the indicated area. In addition, the measured and computed temperatures at each of the ten diffusers are shown.

The overall plenum temperature plot in Figure 23 is consistent with the flow pattern. The first diffuser directly impacted by the inlet jet diffuser has the lowest temperature of all diffusers. The diffuser with the highest temperature is the last impacted by the expanded airflow pattern, which traveled to the far end of the plenum before recirculating back to the nearby diffuser. This analysis helps to explain observations made in many underfloor supply plenum applications. The diffusers closest to the plenum inlet do not necessarily have the lowest temperatures. The temperature rise depends upon the distance that the inlet air travels before reaching the particular diffuser. Due to the complexity of the airflow pattern for a given plenum shape and inlet configuration, the traveled distance is not necessarily the same as the "straight-line" distance between the inlet and diffuser under many conditions.

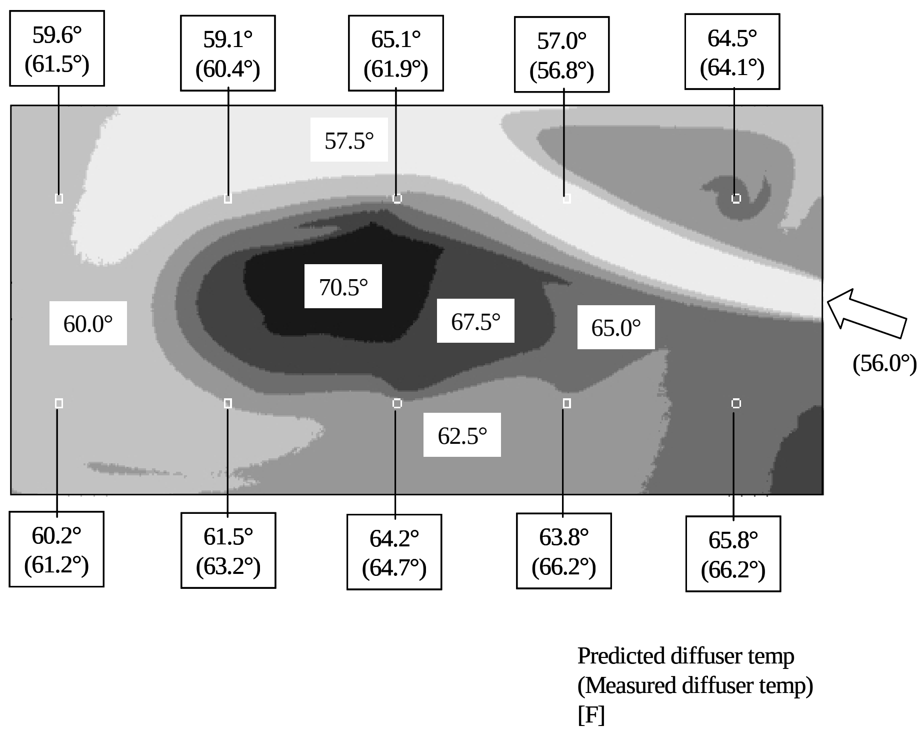

Figure 23. Comparison of measured and CFD-predicted diffuser temperatures for single-focused jet inlet configuration (inch-pound [IP] units)

Table 2 shows the comparison of the total heat gain of the plenum between experiment and CFD prediction. The test facility does not allow the split of total heat gain into heat transfer through the raised floor and concrete slab; the CFD model is capable of providing this relatively detailed information. Agreement for the total heat gain into the plenum is within 7% for the single focused jet and within 5% for the two jets inlet configuration.

Table 2. Comparison of heat gain into the plenum between test and CFD prediction

	One Jet		Two Jets	
	Measured W (Btu/h)	Predicted W (Btu/h)	Measured W (Btu/h)	Predicted W (Btu/h)
Floor	N/A	1,322 (4510)	N/A	1612 (5500)
Slab	N/A	1,753 (5981)	N/A	1379 (4705)
Total	3305 (11,276)	3075 (10,491)	2851 (9727)	2991 (10,205)

Conclusions

The CFD model for the underfloor supply plenum of a UFAD system developed can predict the airflow patterns, air temperature and velocity distributions, and heat flux from the structural slab and the raised floor into the plenum for a variety of thermal and airflow boundary conditions. The model was validated using experimental data collected in a full-scale plenum test facility. The computed air temperature, velocity, and heat flux generally agree well with the measured data. More important, the discrepancies between computed and measured total heat gain of the plenum were less than 10%.

3.3.2. Development of Underfloor Plenum Model for EnergyPlus

This section describes the development of a simplified underfloor plenum model suitable for implementation into EnergyPlus. To this end, the team used the validated CFD plenum model (described in Section 3.3.1) to conduct a larger number of numerical experiments to investigate the energy performance of underfloor plenums over a wide range of realistic plenum configurations and operating conditions. The goal of these CFD simulations was to generate a numerical database to serve as the basis for constructing and testing a simplified plenum model.

CFD Sensitivity Study

Using the validated CFD model, the team simulated nine different plenum configurations to investigate the impact of inlet locations, inlet velocity, total airflow rate, inlet jet direction, and plenum shape on the plenum heat gain and temperature distribution. For most of the cases the modeled plenum had the dimensions of 100 ft by 200 ft by 1 ft high (30.5m x 60.9 x 0.3 m), representing a 20,000 ft^2 (1860 m^2) floor plate of a building.

Figure 24 shows an example schematic diagram of one of the plenum configurations with internal plenum inlet locations, positioned to model two HVAC supply shafts on each end of a building core region. For these simulations, there were 60 diffusers in total, 28 in the perimeter zone and 32 in the interior zone. The primary boundary conditions used for most of the sensitivity analysis cases were as follows:

- Inlet air temperature 16.7°C (62°F)
- Airflow rate = 0.00508 $m^3/s\text{-}m^2$ (1 cfm/ft^2) or 9.44 m^3/s (20,000 cfm) total
- Ceiling temperature = 25.6°C (78°F)
- Ceiling emissivity = 0.9, view factor = 0.5

- Temperature under slab = 26.7°C (80°F)

Simulations were made to investigate the impact of variations in the following parameters:

- Plenum configuration and geometry
- Supply location (e.g., internal, external) and direction
- Airflow rate
- Plenum inlet velocity and temperature
- Ceiling temperature
- Return temperature on the floor below

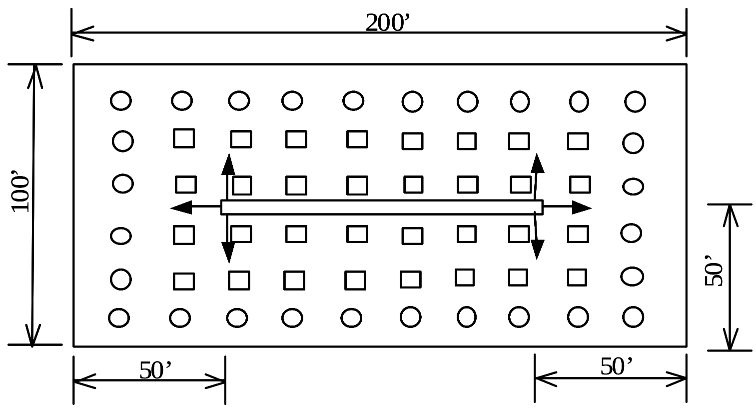

Figure 24. Simulated plenum configuration with internal inlets: square diffusers = interior; round diffusers = perimeter

Results

Table 3 summarizes the results for selected cases with internal inlets simulated with the validated CFD plenum model. The predicted heat transfer variables include the total heat gain to the plenum (through both the concrete slab and raised floor panels), the average surface convection coefficients for each of these two primary surfaces, and the average plenum temperature in both the perimeter and interior zones. The convection coefficients allow calculation of the average heat flux based on the temperature difference between these parameters:

- The average plenum air temperature (assuming a simple well-mixed plenum and calculated as the average of all diffuser temperatures)
- The average surface temperature of either of the two heat transfer surfaces (the underside of the floor panels and the top surface of the slab)

The convection coefficients are based on the detailed CFD results, but were put in simple terms in preparation for implementation into EnergyPlus as described below.

Table 3. Simulated plenum heat gain, convection coefficients and diffuser temperature distribution for internal plenum inlet configurations

Case	Description with Internal Inlets	Inlet Velocity ft/min (m/s)	Heat Gain Btu/h-ft^2 (W/m^2)	Slab Convection Coefficient Btu/h-ft^2-°F (W/m^2-K)	Floor Convection Coefficient Btu/h-ft^2-°F (W/m^2-K)	Average Perimeter Temp °F (°C)	Average Interior Temp °F (°C)
4a	1200 fpm 0.5 cfm/ft^2	1200 (6.1)	3.67 (11.6)	0.34 (1.93)	0.35 (1.99)	69.0 (20.5)	68.6 (20.4)
4b	600 fpm 1 cfm/ft^2	600 (3.0)	5.03 (15.9)	0.45 (2.57)	0.47 (2.67)	65.4 (18.6)	68.1 (20.1)
4c	1200 fpm 1 cfm/ft^2	1200 (6.1)	5.25 (16.6)	0.50 (2.82)	0.58 (3.30)	66.8 (19.3)	67.3 (19.6)
4d	600 fpm 1.5 cfm/ft^2	600 (3.0)	6.05 (19.1)	0.54 (3.09)	0.69 (3.89)	64.8 (18.2)	66.8 (19.3)
4e	1200 fpm 1.5 cfm/ft^2	1200 (6.1)	6.14 (19.4)	0.57 (3.25)	0.70 (3.96)	64.9 (18.3)	66.6 (19.2)
4f	1200 fpm 2 cfm/ft^2	1200 (6.1)	6.80 (21.4)	0.65 (3.67)	0.83 (4.73)	64.2 (17.9)	66.0 (18.9)

Underfloor Plenum Model for EnergyPlus

Figure 25 presents a schematic diagram of the configuration of the simplified plenum model within EnergyPlus:

- Conditioned air from the air handler enters the underfloor plenum (Plenum 1) at the desired flow rate and plenum inlet temperature (T_{in1}).
- As with other conditioned zones, EnergyPlus performs an energy balance on the plenum, producing a single well-mixed temperature ($T_{plenum1}$). To calculate the energy balance, recommended surface convection coefficients, described below, are specified for the slab (h_{s1}) and raised floor (h_{f1}).
- The well-mixed plenum temperature ($T_{plenum1}$) serves as the average diffuser discharge air temperature (T_{out1}) entering the conditioned space (Zone 1).

Note that more than one thermal zone can be served by a single underfloor plenum. In fact, unless the user has more detailed information about the expected temperature distribution in the underfloor plenum across the entire floor plate, a single underfloor plenum is the preferred configuration for each floor of the building. However, if desired, one or more additional plenum zones may be added in series to the first plenum zone.

In this case, as shown in Figure 25, T_{out1} is equal to the plenum inlet temperature (T_{in2}) for the second plenum zone (Plenum 2). This permits the possibility of simulating an interior plenum zone with a cooler supply air temperature and a perimeter plenum zone with a warmer supply air temperature due to thermal decay in the plenum. Note that in this case, the airflow entering the second plenum will be reduced by the volume of air delivered into Zone 1. Due to the complexity of most underfloor plenum airflow and temperature distributions (see

Table 3), until more guidance is available, it is recommended that the user specify a single underfloor plenum per floor

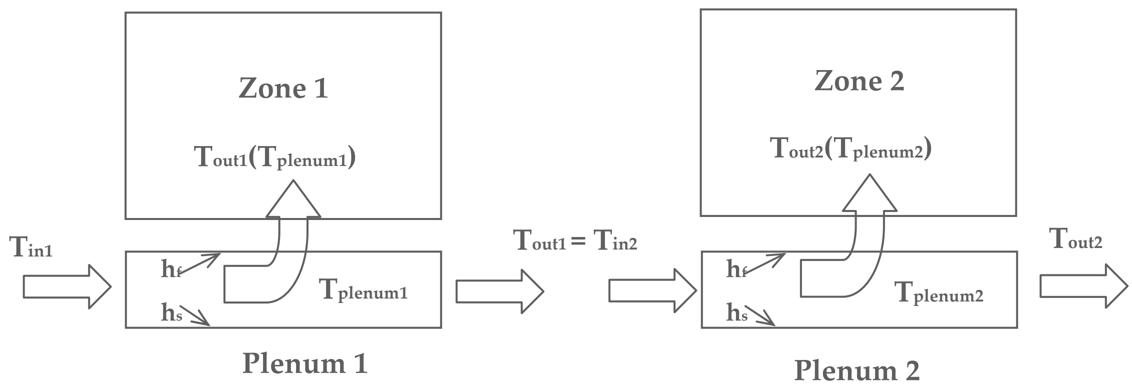

Figure 25. Schematic diagram of EnergyPlus plenum model structure

Full details of the derivation of the final version of the EnergyPlus underfloor plenum model are provided in Appendix D. The final specification of the underfloor plenum model consists of Equations (1) and (2), as listed below, one for the top surface of the slab and one for the underside surface of the raised floor panels.

Bottom surface of underfloor plenum zone (top surface of slab):

$$h_{slab} = 0.1333\,\dot{Q}^3 - 0.58\,\dot{Q}^2 + 0.9567\,\dot{Q} - 0.01 \qquad (1)$$

Top surface of underfloor plenum zone (underside surface of raised floor panels):

$$h_{floor} = 0.16\,\dot{Q}^3 - 0.7\,\dot{Q}^2 + 1.23\,\dot{Q} - 0.11 \qquad (2)$$

where:

h_{slab} = average convection coefficient for top surface of slab (British thermal unit [Btu]/hr-ft^2-°F)

h_{floor} = average convection coefficient for underside of raised floor panels (Btu/hr-ft^2-°F)

$\dot{Q}$ = total airflow rate entering underfloor plenum zone (cfm/ft^2)

The above equations represent a very simplified and approximate model of a very complex airflow configuration resulting in heat exchange with the top and bottom surfaces of an underfloor plenum. Further, underfloor plenum designs will rarely, if ever, conform exactly to the geometric and airflow assumptions upon which this model is based. However, the team believes that in the majority of EnergyPlus simulations, the overall energy balance of an underfloor plenum will be relatively insensitive to all parameters except the total rate of airflow entering the underfloor plenum and will demonstrate reasonable agreement with the predictions of this simplified model. Clearly, further research may provide updated information on this topic in the future.

3.3.3. Simplified Analysis of Heat Transfer Pathways in UFAD Systems

This section reports on a modeling study to investigate the primary pathways for heat removal from a room with UFAD under cooling operation. Compared to the standard assumption of a well-mixed room air condition, stratification produces higher temperatures at the ceiling level that change the dynamics of heat transfer within a room, as well as between floors of a multi-story building. A simplified first-law model was used to estimate and compare the relative magnitudes of the heat being removed from a room through two primary pathways:

- Heat extraction via warm return air exiting the room at ceiling level or through the return plenum
- Heat entering the underfloor supply plenum either through the slab from the floor below or through the raised floor panels from the room above

The goal of the study was to seek evidence that supports two surprising and widely observed thermal phenomena in UFAD systems:

- The return air extraction rate based on the temperature difference between the room return and diffuser supply air temperatures is almost always noticeably less than the total room cooling load based on the sum of all space heat gains.
- Temperature gain (thermal decay) in open underfloor supply plenums is often larger than expected.

The modeling results were consistent with these observations and also provided guidance to the research team towards development of the new version of EnergyPlus/UFAD, described in the Appendix D.

Description of Simplified Model

The simplified first law model was configured to calculate (or use assumed values for) inlet and outlet air temperatures for two control volumes:

- The room, bounded by the top of the raised floor and the underside of the slab (with or without insulation)
- The underfloor plenum, bounded by the top surface of the slab and the underside of the floor panels

For the room/return plenum, the model performs a steady state heat balance on each of the three major architectural layers of the heat transfer system:

- Top surface of raised floor (carpet)
- Bottom surface of slab (or slab insulation, if present)
- Suspended ceiling (if present—assumed to be a uniform temperature (infinite conductivity))

In addition, heat balances are also performed on the top and bottom surfaces of the supply plenum, representing the bottom surface of the raised floor panels and the top surface of the slab, respectively. Figure 26 shows a schematic diagram of the modeled configuration, representing one floor of a multi-story building.

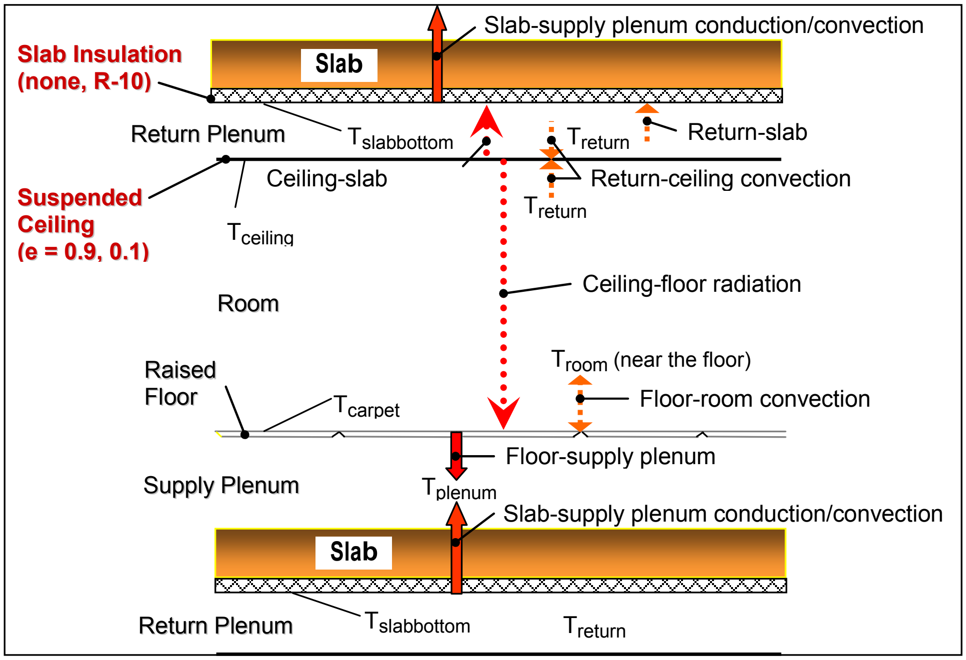

Figure 26. Schematic diagram of heat transfer pathways in room with UFAD and hung ceiling

As indicated in the Figure 26, the calculations by the simplified model consider the following heat transfer processes:

- Conduction through the slab and floor panels, as well as into the supply plenum via convection.
- Radiation from the ceiling to the raised floor (and from the top of the hung ceiling to the underside of the slab).
- Convection between the return air and the suspended ceiling and/or the ceiling/slab. (The return temperature, after losing heat to the slab, is assumed to be the same as the temperature within the well-mixed ceiling plenum (when present), as well as near the top of the room (with or without suspended ceiling)).
- Convection between the room air near the floor and the raised floor panels (carpet surface).

To investigate possible strategies for reducing the magnitude of energy transferred into the underfloor plenum, the model was configured to include different combinations of a low emissivity ceiling and slab insulation. These ceiling thermal properties were applied to both a suspended ceiling and an open, exposed slab (no hung ceiling), as outlined for Cases 1–3 in Table 4 below.

Table 4. Properties of ceiling configurations investigated with simplified model

Ceiling Condition	Baseline	Case 1	Case 2	Case 3
Emissivity (ε_c) = 0.9	X		X	
No slab insulation	X	X		
Emissivity(ε_c) = 0.1		X		X
Slab insulation = R-10			X	X

To conduct the model simulations, initial air temperatures, representing baseline conditions, were selected to provide a typical vertical temperature profile for a well-stratified interior zone of a building, such as those described by Webster et al. (Webster et al. 2002a, 2002b). For this profile, the temperature near the ceiling, representing the return air temperature, was assumed to be 25.6°C (78.0°F) and the temperature near the floor was assumed to be 22.2°C (72.0°F), producing a 3.4°C-(6.0°F-) temperature gradient from floor to ceiling. In addition, the average supply air temperature leaving the underfloor plenum was 18.3°C (65.0°F), and the room airflow rate was 3.05 L/s-m^2 (0.6 cfm/ft^2).

Results

Figure 27 presents a summary of the room cooling load distribution with hung ceiling, as predicted by the model. The figure allows easy comparison of the relative proportions of energy leaving the room through the two primary pathways:

- Heat extraction via warm return air exiting the room at ceiling level or through the return plenum
- Total heat transferred to the underfloor supply plenum (through the slab and raised floor panels)

Note that in Figure 27, 100% represents the heat gain to the room (i.e., the source of the loads) that leaves via return air extraction and heat transfer to the plenum. It is synonymous with the total energy leaving the system comprising the room and supply plenum. As shown for the baseline case, representing standard construction practice, 42% of the total room cooling load leaving the space exits into the supply plenum and only 58% is accounted for by the return air extraction rate. These findings demonstrate why temperature gain in supply plenums can be a problem. Of the energy entering the underfloor plenum, twice as much (28%) is calculated to enter through the slab compared to the raised floor (14%). The results for Cases 1–3 demonstrate that use of two ceiling thermal treatment strategies—an R-10 insulation layer on the underside of the structural slab and low-emissivity (ε_c=0.1) coating applied to the top and bottom surface of a hung ceiling—can reduce the magnitude of energy transferred into the underfloor plenum. Further results and sensitivity analysis of the model assumptions are discussed in Appendix D..

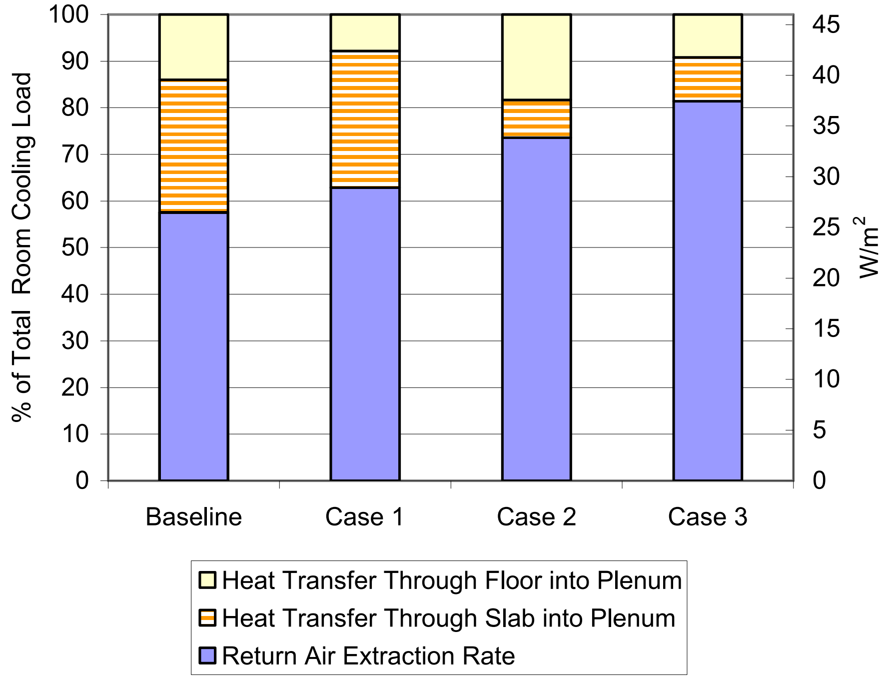

Figure 27. Predicted percentage of total room cooling load and amount (W/m^2) of energy flows leaving room with UFAD and hung ceiling; room airflow rate = 3.1 $L/s\text{-}m^2$ (0.6 cfm/ft^2)

Conclusions

A simplified heat balance model was used to estimate and compare the amount of energy being removed from a stratified room with a UFAD under cooling operation. Surprisingly, for the range of cases studied, findings show that for typical multi-story building configurations (raised access floor on structural slab with or without suspended ceiling), 30–40% of the total room cooling load is transferred into the supply plenum and only about 60–70% is accounted for by the return air extraction rate. These findings have important implications for the design, operation, and energy analysis of UFAD systems.

In a stratified UFAD system, the return air extraction rate based on the temperature difference between the room return and diffuser supply air temperatures will always be significantly less than the total room cooling load based on the sum of all space heat gains.

Cooling airflow design calculations must account for the distribution of room cooling load between the underfloor supply plenum and the room. The results of this study were directly used in the team's subsequent development of a new UFAD cooling airflow design tool, as described in Appendix F.

The amount and distribution of temperature variations in the underfloor supply plenum can significantly impact the cooling operation of a UFAD system. This finding is especially true in perimeter zones, where increased diffuser supply temperatures can make it more difficult to satisfy peak cooling loads.

Slab insulation proved to be the most effective strategy among those investigated for reducing supply plenum heat gain in a multi-story building.

Simulations at higher airflow rates demonstrated reduced temperature gain in the plenum and stratification in the room, albeit at the cost of higher fan energy use. Future research is needed to address some of the control strategy trade-offs suggested by this result. For example, optimizing performance may involve trading-off fan energy savings from reduced airflow vs. economizer savings (in suitable climates) from increased airflow and greater coil leaving air temperatures. This will be the subject of future research with the new version of EnergyPlus/UFAD described in this final report.

3.4. EnergyPlus Module Development and Validation

EnergyPlus additions and enhancements for the UFAD project consist of 3 major pieces:

- Upgrades to HVAC system simulation capabilities
- Interior and exterior non-uniform zone models
- Supply plenum modeling

Each of these pieces needs to be available before a complete UFAD system can be simulated. UFAD systems are not just systems with a funny air supply. They are equipped with their own specialized types of equipment, HVAC configuration, and control. This section of the report describes the EnergyPlus upgrades made as a result of this project.

3.4.1. HVAC System Upgrades

At the start of the UFAD project, two HVAC modeling capabilities not yet in EnergyPlus were identified as vital for UFAD simulation: a variable-speed fan terminal unit and return air bypass capability.

At project inception, EnergyPlus had a variety of terminal unit component models. None had the capability of simulating a VAV terminal unit with a variable speed fan (and heating coil)—a unit often used to supply UFAD exterior zones. Both core project members (Tom Webster) and by advisory team members (Taylor Engineering) determined that this component was critically important to simulating realistic UFAD systems. T

EnergyPlus has theoretically general HVAC duct configuration capability, but the allowed configurations have been limited in practice. At project startup, EnergyPlus could simulate single splitters on the air-system supply side: basically single and dual duct systems. No provision existed for a mixer and splitter, as would be needed for a return air bypass (RAB) system or any means for controlling such a system. The ability to model RAB configurations was identified as a key feature for UFAD systems. Such systems have higher than normal supply air temperatures. As a consequence, a conventional single duct setup would have difficulty removing sufficient moisture from the mixed air to maintain comfortable zone humidity levels. RAB configurations are often used in UFAD systems to mitigate this problem.

The following sections describe work done in the above two areas. A full Users Description and Engineering Documentation, as well as example files, can be found in Appendix E.

Variable Speed Fan Terminal Unit Model

The variable speed fan terminal unit in EnergyPlus exhibits a number of features not available in the other terminal unit models. It contains a variable speed fan that can control the flow of cool or reheated supply air to the zone. It also has separate maximum cooling and heating air flow rates. And the model is fully iterative—it makes no assumptions about the linearity of its subcomponent models. The model inputs and calculations are fully described in Appendix D. An example of the model's use is contained in example input 5ZoneSupRetPlenVSATU.idf. This model was released with EnergyPlus 1.2.1 in October 2004.

Return Air Bypass Capability

Creating the capability to model RAB duct configurations in EnergyPlus required a number of new components and upgrades:

- Air primary loops needed the capability to contain mixers. Accordingly, programmers added mixers to the data structures, input, and initialization code written, and added the ability to simulate mixers.
- The air side simulation needed to be able to simulate bypass branches, or branches with no functional component. To enable this the pass-through component, duct was created, analogous to the pipe component in plant.
- The flow rate through the bypass branch needed to be controlled. To do this the new setpoint manager, SET POINT MANAGER:RETURN AIR BYPASS FLOW, was created.

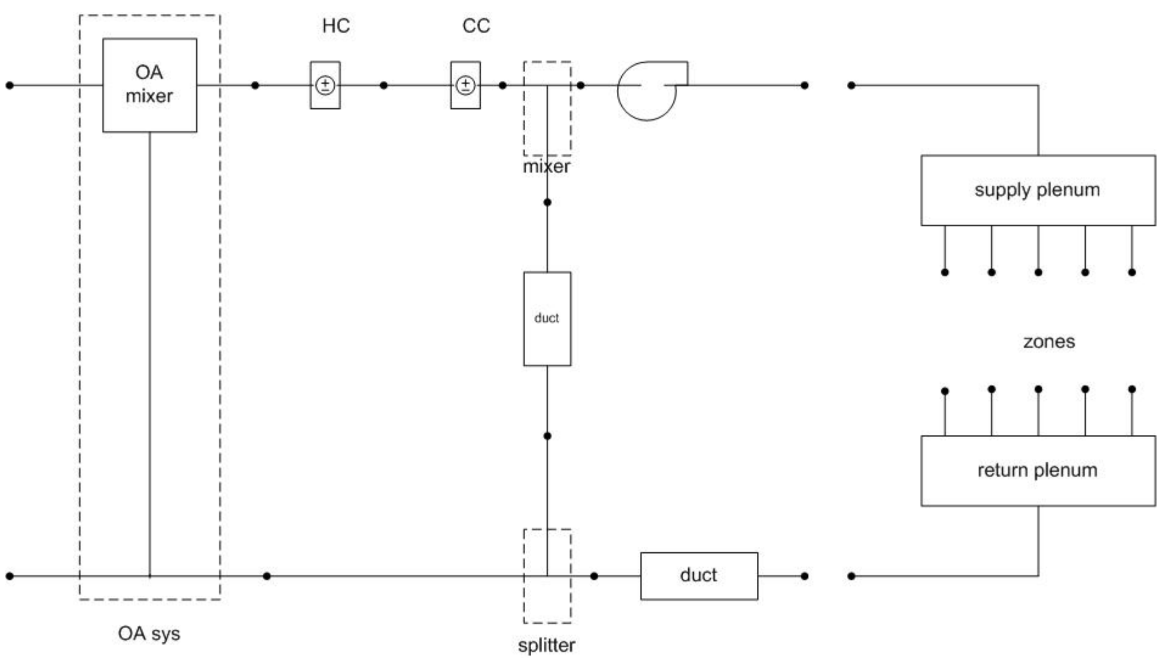

Figure 28. Simple RAB Configuration showing mixer, splitter, and duct

The complete RAB simulation capability was released with EnergyPlus version 1.2.3 in October 2005. An example input illustrating the capability is *5ZoneSupRetPlenRAB.idf*. The individual components used for RAB are described in Appendix E.

3.4.2. New UFAD Models in EnergyPlus

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
- The UCSD models, which divide the zone vertically into sub-zones with thicknesses depending on load and air flow rate

For the UFAD project, two new room air models have been developed: interior UFAD and exterior UFAD. Both are tow-node (two sub–zone) models similar to the UCSD Displacement Ventilation model. The two models are described below and in the E.

A major barrier to modeling UFAD systems has been the inability to model supply air plenums. In the early phases of the UFAD project, EnergyPlus was enhanced to permit the a general configuration of supply plenums in the supply air path. This enhancement gave the program the capability of trying various series and parallel supply plenum configurations. The plenums were still modeled as well-mixed zones with a single average air temperature. Temperature decay could be modeled by concatenating plenums in series. It was believed that treating supply plenums as normal zones would prove to be inadequate. However EnergyPlus simulations compared to measurements and CFD simulations (carried out by CBE) showed that simply varying the convection coefficients at the upper and lower surfaces produced good agreement. The EnergyPlus supply plenum modeling capabilities are described below and in Appendix E.

UFAD Interior Room Air Model

In EnergyPlus the default zone model is a uniform, well-mixed zone. To specify such a zone, the user needs only to enter a Zone object in the input file. In order to choose a nonuniform zone model, a RoomAirModel object needs to be specified. This object allows the user to choose from among a variety of nonuniform models: well mixed, user defined nodal model, Mundt nodal air model, UCSD three-node displacement ventilation model, UCSD two-zone cross ventilation model, UCSD 2-node UFAD model for interior zones, and UCSD 2-node UFAD model for exterior zones. Each choice requires further input specific to the model chosen. For UCSD UFAD Interior the additional input is specified in a UCSD UFAD Interior Model Controls object. This input is described in Appendix E.

Modeling UFAD interior zones required a number of changes and enhancements to EnergyPlus. simulation of nonuniform zones in EnergyPlus is centralized in the module *RoomAirModelManager*. This module handles obtaining the room model input data, model initialization, and calling the individual model management routines. For the UCSD UFAD interior zone model, a new “get input” routine *GetUFADZoneData* was written (which also processes the exterior zone model input), initializations for the interior zone model were added to subroutine *SharedDVCVUFDataInit* , and a call to the model manager *ManageUCSDUFModels* added.

The data structures and arrays for UCSD UFAD interior model controls and UCSD UFAD exterior model controls are contained in the data-only module *DataRoomAir*. The relevant arrays are *ZoneUCSDUI* and *ZoneUCSDUE*.

For modeling the UFAD zones an entirely new module was created: UFADManager. This module contains the routines *ManageUCSDUFModels*, *InitUCSDUF*, *SizeUCSDUF*, *HcUCSDUF*, *CalcUCSDUI*, and *CalcUCSDUE*. These routines accomplish the following tasks:

- *ManageUCSDUFModels*: acts as the access point to the module. It is the only **Public** routine in the module. Calls *InitUCSDUF* and *CalcUCSDUI* or *CalcUCSDUE*.
- *InitUCSDUF*: does local, module initialization. Most of the initialization is done at the higher level in *RoomAirModelManager*. Calls *SizeUCSDUF*.
- *SizeUCSDUF*: sets input defaults depending on the zone model and diffuser type. See code in Appendix 4 for specifics.
- *HcUCSDUF*: sets the convection coefficients for the room surfaces – basically uses free convection values.
- *CalcUCSDUI*: calculation of UFAD interior zone subzone boundary height and subzone temperatures. The calculation is well described in the Engineering Reference section in Appendix D.

Although most of the changes made to EnergyPlus in order to model UFAD interior and exterior zones are well encapsulated in the modules *RoomAirModelManager* and *ManageUCSDUFModels*, some changes to other parts of the code were needed as well.

UFAD Exterior Room Air Model

In terms of software, the UFAD exterior zone is modeled in a similar manner to the interior zone. The input and most of the initialization occurs in *RoomAirModelManager*. Defaulting of inputs is done in *RoomAirModelManager*, subroutine *SizeUCSDUF*. Convection coefficients are calculated in *RoomAirModelManager*, subroutine *HcUCSDUF*. Calculation of subzone boundary height and subzone temperatures is done in *RoomAirModelManager*, subroutine *CalcUCSDUE*.

In terms of physical processes, the situation in the exterior zone is more complex (plumes coming from window surfaces as well as workstations). And the equipment used may be different (linear bar grille diffusers for instance). As a result the input and calculations are slightly different from the interior zone case bit the overall scheme is the same.

Underfloor Plenum Model

As a result of the work done by CBE in measuring conditions in a test plenum and in simulating various plenum configurations using CFD, the supply air plenums are treated as normal well-mixed zones in EnergyPlus. Depending on the supply air flow rate, different convection coefficients should be used on the plenum upper and lower surfaces. These convection coefficients will need to be input using the ConvectionCoefficients object.

In summary, to describing an underfloor plenum in EnergyPlus requires the following steps:

- The plenum needs to be described geometrically as a zone in the overall geometric description of the building. This means there should be a Zone object for each plenum and there should be appropriate associated Surface:HeatTransfer objects describing the shape of the plenum and how it connects to the other zones in the building.
- The plenum should be treated as a well-mixed zone. There should be no RoomAir Model associated with the plenum zone.
- There must be a Zone Supply Plenum object for each supply plenum. It must reference the relevant zone and be referenced in the Zone Supply Air Path for the system. The Zone Supply Air Path can contain any number of Zone Supply Plenums and Zone Splitters. This enables a general branching configuration in the supply air path. The connectivity is defined direct inlet/outlet node connections. The program does check for correct connectivity.
- ConvectionCoefficients object values should be entered with recommended values for the supply plenum upper and lower surfaces.

The capability to link Zone Supply Plenums and Zone Splitters in a general configuration in the Zone Supply Air Path was added to EnergyPlus as part of this project.

3.4.3. Validation of New Models in EnergyPlus

Interior RAS model

Validation was attempted by comparing EnergyPlus results with extensive measurements made at the York test facility by York and CBE. The effort is described in Appendix E. The first step was to match test chamber results with EnergyPlus for the well-mixed case. These runs were made by Alan Daly of Taylor Engineering (who wrote a custom interface for EnergyPlus to facilitate the runs) and were eventually successful. Then comparisons were made with various UFAD test runs at the York test chamber. These comparisons are not completely successful; there is generally good agreement in supply and return temperatures, but often difficulty matching the occupied subzone temperatures. Reasonable agreement in the occupied subzone comes only when the "fraction of the occupied subzone gains that remain in the subzone" parameter is between 0.75 and 1.0.

Exterior RAS model

Validation for the exterior model is incomplete. It should be noted that the artificial sun/window setup at the York test facility introduced a major modeling issue into this validation effort. Early on in the project, it was decided to avoid modeling the window by using test chamber interior glass temperature measurements and interior surface radiation flux measurements directly in EnergyPlus. A modified version of EnergyPlus was created to enable direct use of these measurements. Two new objects were created: *MeasuredUFADWindowData* and *MeasuredUFADSolarFraction*. The modifications and new objects are described in Appendix E.

Underfloor Plenum Model

Blind comparisons were done between EnergyPlus runs performed at LBNL and CFX simulations and measurements performed by CBE. Two main configurations were tested:

1. A 22 by 48 foot floor plan with a single 1 foot high supply plenum. This is basically the layout of the CBE plenum test facility.
2. A 50 by 100 foot floor plan divided into 2 zones: 35 x 100 (south) and 15 x 100 (north). In this case the larger zone represents an interior zone and the smaller zone an exterior zone. Air is supplied first to the interior zone, then to the exterior zone. Hence the supply air temperature will be higher for the exterior zone. This is a test of EnergyPlus' capability to model temperature rise in a supply air plenum.

For case 1, the team can provide the following results. The comparison is between measured, CFX and 3 EnergyPlus runs. EnergyPlus run 4 has radiative exchange between the supply plenum ceiling and floor turned ON, and uses $h_{c,ceiling}$ = 4.01 (W/m^2K), $h_{c,floor}$=3.52. Run 5 has the same h_c's, but turns the radiative exchange between the ceiling and floor OFF (to match the CFX simulations). Run 6 has the radiation exchange OFF and uses $h_{c,ceiling}$=7.66, $h_{c,floor}$=4.72. The results from these the 3 EnergyPlus runs are shown in Table 5 and give some idea of the sensitivity of the results.

Table 5: Plenum sensitivity study, Case 1

	Supply Plenum Temperature (°C)	Supply Plenum heat gain (W)	Plenum Ceiling Heat Gain (W)	Plenum Floor Heat Gain (W)	Plenum Ceiling Temperature (W)	Plenum Floor Temperature (W)
CFX1	16.7	3075				
CFX2		2996	1243	1753		
Measured	17	3305				
Eplus4	16.85	3187	1589	1597	20.89	21.48
Eplus5	16.82	3159	1426	1733	20.45	21.83
Eplus6	17.25	3553	1649	1904	19.45	21.37

Table 6: Plenum sensitivity study, Case 2

	Interior Supply Plenum Temperature (°C)	Exterior Supply Plenum Temperature (°C)	Interior Supply Plenum Heat Gain (W)	Exterior Supply Plenum Heat Gain (W)
CFX	19.2	20.3	7063	1560
EnergyPlus	19.3	20.3	7415	1599

The EnergyPlus inputs for these comparisons are given in Appendix E.

3.5. Cooling Airflow Design Tool

Design engineers often cite methods for airside design sizing as one of the most important unanswered questions regarding UFAD system design. The determination of design cooling air quantities must take into account key differences between a thermally stratified space and a conventional well-mixed space. The following report on the cooling airflow design tool describes:

- The development of the calculation methods that form the basis for the modeling engine
- User inputs and outputs
- Preliminary validation by comparison to full-scale experimental data
- Example results to demonstrate the behavior and sensitivity of the design tool to different user inputs and assumptions
- Comparison to overhead system airflow quantities for equivalent comfort conditions
- Future work needed to improve and refine the design tool

For the full report, see Part VI of the Final Report.

3.5.1. Development of Design Tool

A design tool developed is a spreadsheet-based calculation procedure that in its final form will be easy to use by practicing design engineers. Figure 29 shows the current scheme for the design tool process. Inputs include the standard output from a load calculation tool and a number of room description parameters. The model can then determine cooling airflow, thermostat setting to achieve a given comfort condition, the air temperature to be supplied to the underfloor plenum, and the airflow to be used for a conventional overhead system given the same load conditions.

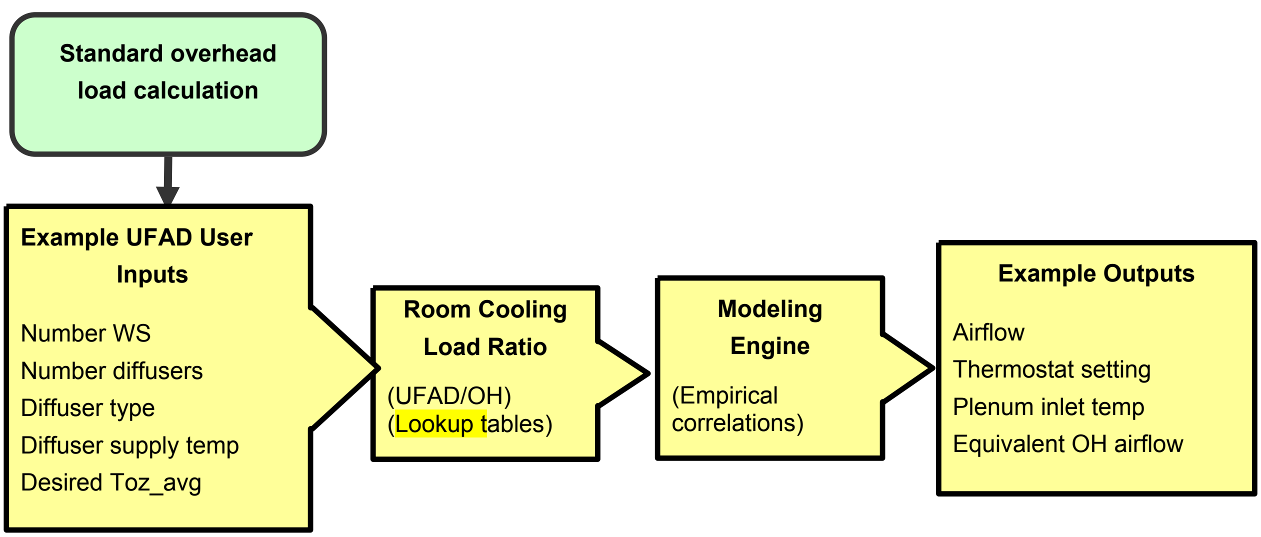

Figure 29. Design tool schematic

Figure 30 shows an example of the simplified temperature profile calculated by the design tool compared to full-scale measured data. The vertical temperature difference between head height (170 centimeter [cm] or 67") and ankle height (10 cm or 4"), ΔT_{oz}, should not exceed 2.7°C (5°F), as specified by ASHRAE Standard 55-2004 (ASHRAE 2004). The average temperature in the occupied zone, $T_{avg, oz}$, is determined based on the temperature profile between 10–170 cm (4–67").

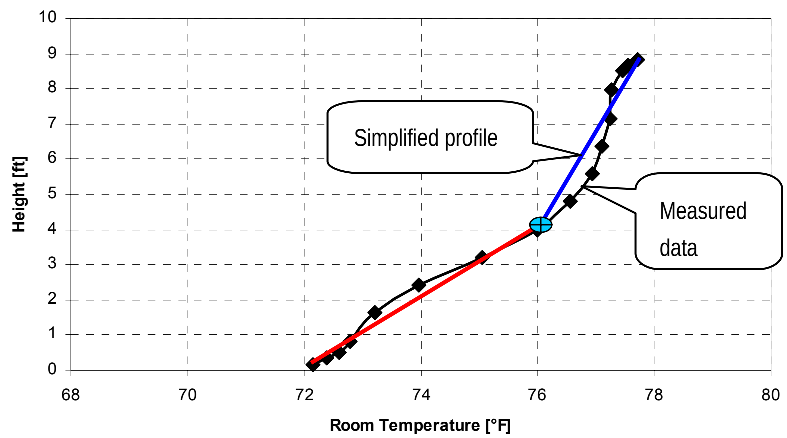

Figure 30. Simplified temperature stratification profile

3.5.2. Model Behavior

As the design tool development has progressed, the team compared the tool's performance to the current understanding of UFAD systems when subjected to a variety of conditions to ensure that the tool was producing intuitive and accurate results.

Sensitivity studies

Variation of Load

One of the user inputs to the design tool will be the cooling load as derived from a standard load calculation procedure. Assume that the goal of the designer is to use an airflow that would yield an average occupied zone temperature ($T_{oz, avg}$) of 22.7°C–23.8°C (73°F–75°F) and an occupied zone stratification (ΔT_{oz}) of 1.6°C–2.7°C (3°F–5°F), then the model can be used to explore a range of load conditions to determine airflows that will satisfy these comfort criteria. In Figure 31–33, , $T_{oz, avg}$ and ΔT_{oz} are plotted against airflow (cfm/ft^2) for three different load conditions in the space based on design tool results assuming a swirl diffuser, one diffuser per workstation, and an 18.3°C (65°F) diffuser discharge temperature (Ts).

The blue shaded region is the range of airflows that satisfy the $T_{oz, avg}$ design condition (22.7°C–23.8°C or 73°F–75°F) and the red shaded region is the range of airflows that satisfy the ΔT_{oz} design condition (1.6°C–2.7°C or 3°F–5°F). Where the two overlap is the range of airflows that satisfy both design conditions. The model incorporates a room cooling load ratio, R, defined as the percentage of the overhead (OH) cooling load that is to be assigned to the room in the

UFAD airflow calculation. Since research has shown that about one third of the load is transferred into the underfloor plenum (Bauman et al. 2006), this has the effect of reducing the amount of load that must be removed by the room airflow quantity. The team used a value for R of 70% for all of these studies.

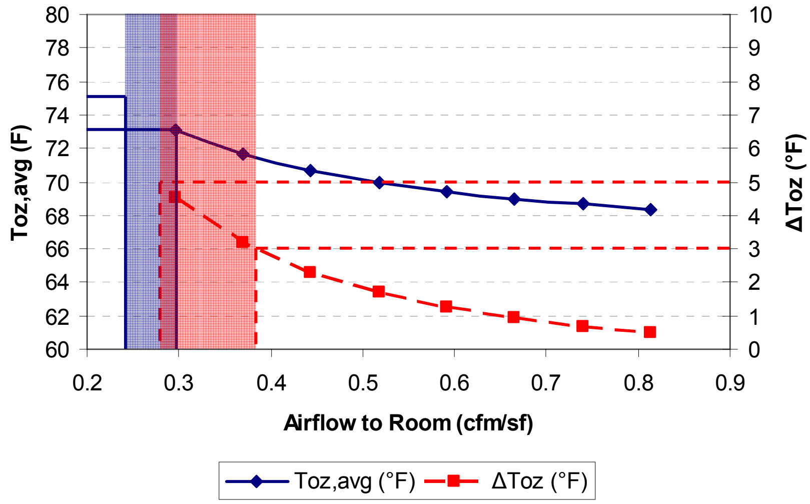

Figure 31. Design conditions vs. airflow, at a cooling load of 1.5 W/ft2

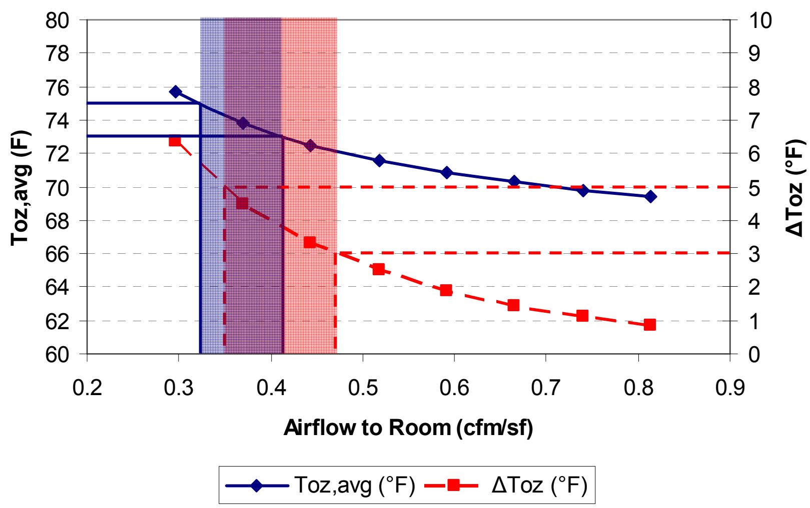

Figure 32. Design conditions vs. airflow, at a cooling load of 2.0 W/ft2

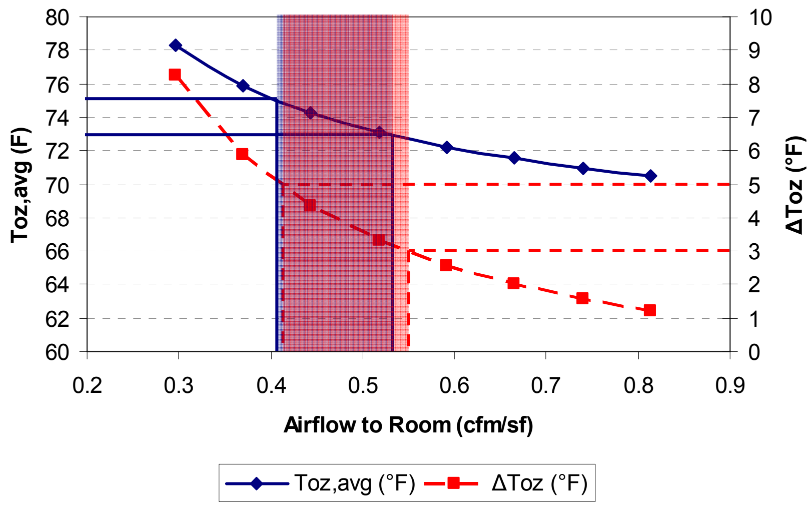

Figure 33. design conditions vs. airflow, at a cooling load of 2.5 W/ft2

Raising the load in the space alters the location of the $T_{oz,\ avg}$ line, indicating that as the load is raised, more air is needed to maintain the average occupied zone temperature at the same level. Figure 31 shows that at a load of 1.5 W/ft^2 , an airflow of approximately 0.3 cfm/ft^2 would be needed to satisfy the design conditions, whereas Figure 33 shows a situation where approximately 0.4–0.5 cfm/ft^2 would be required to meet design conditions. As the load is increased (from 1.5 W/ft^{2}in Figure 31 to 2.5 W/ft^2 in Figure 33), more air is needed to keep the $T_{oz,\ avg}$ within design limits. However, the temperature stratification is less affected by the higher loads, as indicated by the relatively lesser movement of the red column with respect to the blue column. Horizontal discharge and variable area systems show the same pattern.

Variation of Number of Diffusers

The design tool also allows the user to input the number of diffusers per workstation in the space. As more diffusers are added for the same total room airflow, each diffuser delivers less air, thereby reducing the diffuser throw and amount of mixing in the room. For most UFAD installations it would be expected that one diffuser/workstation, plus a few more for corridors and other open use spaces, would result in values between 1–1.5 diffusers/workstation.

Using the model to generate similar plots (see Appendix F) to those in the previous section, as more diffusers are added to the space, the model predicts that less airflow will be needed to maintain the desired average temperature in the occupied zone, but more airflow is needed to maintain the stratification desired. Again, this pattern is the same for the horizontal discharge and variable area conditions, though the values vary.

Variation of Supply Air Temperature

The current version of the design tool assumes that the average air temperature leaving the supply plenum (at the diffusers, Ts) is set at 18°C (65°F). Using the model to generate similar plots to those shown in the Variation of Load section (see Appendix F), as the supply temperature is increased, the stratification curve is unaffected and more airflow is required to satisfy the average temperature design condition. If the supply air temperature is raised much more, it is again impossible to satisfy both design conditions. Additionally, as the supply air temperature is increased, the sensitivity of average temperature to changing airflow decreases.

Figure 34 shows variations in the supply plenum entering temperature (Tsplenum) as a function of changes in the diffuser discharge temperature (Ts) and airflow rate. Altogether, the design tool leads to the conclusion that satisfying design conditions requires use of either a supply temperature (diffuser discharge temperature, Ts) of 18°C (65°F) at an airflow of 0.42 cfm/ft^2–0.53 cfm/ft^2 or a supply temperature of 19.4°C (67°F) at an airflow of 0.53 cfm/ft^2–0.55 cfm/ft^2.

Taking this information to Figure 34, the 18°C (65°F) condition requires that the air temperature entering the plenum (Tsplenum) be between 15.2°C–15.8°C (59.5°F–60.5°F) whereas a 19.4°C (67°F) condition requires a Tsplenum between approximately 16.7°C–16.9°C (62.2°F to 62.5°F). In short, the design tool shows that one can meet the design conditions by either using a smaller quantity of cooler air, or a larger quantity of warmer air. For the complete set of figures, see Appendix F.

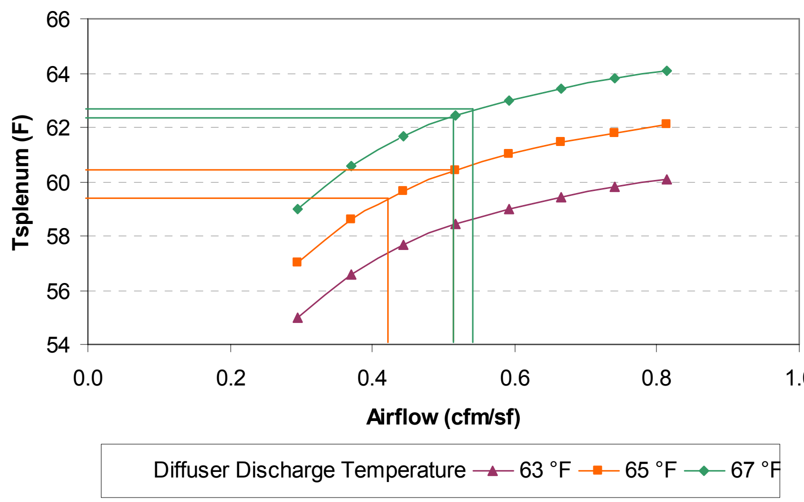

Figure 34. Air temperature entering supply plenum (Tsplenum) vs. airflow for different diffuser discharge temperatures

Comparison to Overhead Airflow

The design tool will also be capable of calculating the range of airflows that would be used in a comparable OH system subject to the same loads and attempting to meet the same average temperatures as that of the occupied zone in the UFAD case. Initial studies have shown that this airflow range is close to the predicted airflow required to meet the design conditions for UFAD and often overlaps when one uses an overhead supply air temperature between 12.7°C–13.8°C

(55°F–57°F). One example is shown below in Figure 35. In this figure, the dashed box represents the overhead airflow needed to achieve an average temperature in the room of 22.7°C–23.8°C (73°F–75°F) assuming a supply air temperature of 12.7°C–13.8°C (55°F–57°F) and a load of 2 W/ft². The UFAD case assumes a diffuser discharge (Ts) temperature of 65°F. Although difficult to read in the figure, the zones of acceptable airflow are as follows:

- UFAD system: 0.35–0.41 cfm/ft²
- OH system: 0.31–0.39 cfm/ft²

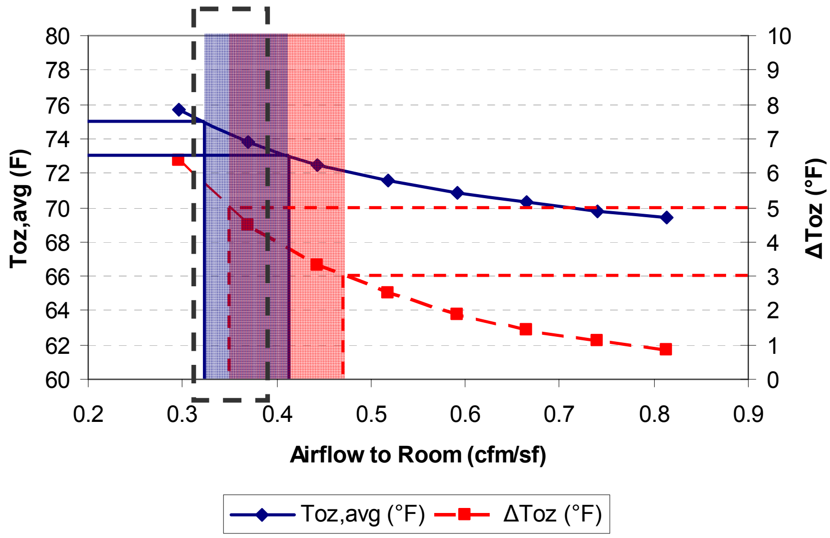

Figure 35. Example of comparison to overhead airflow

3.5.3. Further Explorations

A number of other explorations of the design tool are shown in the extended report in Part VI of The Final Report, including the following:

- Room cooling load ratio
- Comparison of $T_{oz,avg}$ to T_{set}
- Comparison of model calculations to test data

4.0 Conclusions and Recommendations

This final report described the results and deliverables from a multi-year research project, sponsored primarily by the CEC PIER Buildings Team, to develop a version of the publicly available whole-building energy simulation program, EnergyPlus, capable of modeling underfloor air distribution systems. A second major deliverable from this project was the development of a practical design tool for determining the cooling airflow quantity for UFAD systems. With the completion of this project, the new version of EnergyPlus, called EnergyPlus/UFAD, and the cooling airflow design tool are the first validated UFAD tools of their kind and represent a significant advancement in the state-of-the-art of UFAD system design and energy analysis.

As part of the effort to develop EnergyPlus/UFAD, members of the research team have focused their efforts on two key issues (room air stratification and underfloor plenums) in the design and cooling operation of a UFAD system in a multi-story building. Both represent areas where UFAD differs from conventional overhead systems, with important implications for designing, operating, and modeling UFAD systems, as summarized below.

- **Room air stratification**: Under cooling operation, properly controlled UFAD systems produce temperature stratification in the conditioned space resulting in higher temperatures at the ceiling level than at the floor. In contrast to the well mixed conditions provided by OH systems, stratification requires a new approaches for the following:
    - Modeling the space temperature, as a single temperature node is no longer valid.
    - Defining comfort in the occupied zone, as a single 4-ft thermostat temperature is no longer representative of average comfort conditions (see below).
    - Modeling heat transfer pathways in UFAD systems with underfloor plenums, as stratification leads to a significant amount of energy entering the underfloor plenum (see below).
- **Thermal performance of underfloor plenums**: Cool supply air flowing through the underfloor plenum is exposed to heat gain from both the concrete slab and the raised floor panels. The magnitude of this heat gain can be quite high, resulting in undesirable loss of control of the supply air temperature from the plenum into the occupied space (sometimes referred to as thermal decay). Under cooling operation in a multi-story building, heat leaves the room through two primary pathways:
    - Heat extraction via warm return air exiting the room at ceiling level or through the return plenum
    - Heat entering the underfloor supply plenum either through the slab from the floor below or through the raised floor panels from the room above

  Surprisingly it was shown that 30–40% of the total room cooling load is transferred into the supply plenum and only about 60–70% is accounted for by the return air extraction rate, or cooling airflow quantity.

- **Equivalent comfort conditions**: For purposes of allowing a comparison between energy simulations or cooling airflow calculations for a stratified system with UFAD vs. OH systems, it is important to define an equivalent comfort condition for a stratified room as follows:
    - o The average occupied zone temperature ($T_{oz,\ avg}$), calculated as the average of the measured temperature profile from foot level (10 cm or 4 in.) to head level (170 cm or 67 in.), is equal to the desired setpoint temperature (as measured in a well-mixed OH system).
    - o The occupied zone temperature difference (ΔT_{oz}), calculated as the head-foot temperature difference, does not exceed the maximum limit specified by ASHRAE Standard 55 of 2.7°C (5°F).

In a coordinated effort, the research team conducted 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 for room air stratification and one for underfloor plenums. The RAS model was supported by small-scale salt tank testing, an analytical model to improve theoretical understanding, and full-scale laboratory testing to provide realistic data for comparison and model validation. The underfloor plenum model was supported by full-scale testing and a CFD plenum model, which was validated by comparison with the full-scale testing database. This coordinated approach has proven to be very successful, as the EnergyPlus validation studies completed to date have demonstrated good agreement with experimental and CFD-predicted data. In addition, the large amount of supporting research has produced a vast amount of new knowledge and improved understanding of the fundamental principles of UFAD system design, operation, and energy performance.

4.1. Commercialization Potential

Both of the major deliverables from this project, EnergyPlus/UFAD and UFAD Cooling Airflow Design Tool, do not represent products suitable for commercialization efforts. EnergyPlus is a publicly available computer program (www.energyplus.gov), whose development and maintenance is supported by the U.S. Department of Energy. Similarly, the design tool has been developed at a public institution, UCB, with public PIER funding, and will be made available to the public through subsequent publications in the engineering literature (e.g., ASHRAE).

4.2. Recommendations

As expected in a challenging and groundbreaking research project of this kind, not all model development goals were achieved to a level of accuracy and validity originally envisioned when the project was started. A list of recommended refinements and improvements to both EnergyPlus/UFAD and the Cooling Airflow Design Tool are identified below.

The recommended activities in support of improving and refining EnergyPlus/UFAD include the following:

- Complete improvement and refinement of interior zone RAS model. This work includes consideration of what portion of the room heat gain is assigned to the thermal plume model, specification of the lower (occupied) and upper zone temperatures, determination of room thermostat control temperature, determination of appropriate stratification height separating the lower and upper zones, and determination of representative comfort conditions (average occupied zone temperature and head-foot temperature difference).

- Complete improvement and refinement of perimeter zone RAS model. In addition to the RAS model efforts recommended above, this work must consider the window plume model when solar loads are dominant, as well as the distribution of the transmitted solar radiation through perimeter windows.
- Complete the validation of both the improved interior and perimeter RAS models by comparison with full-scale data from the York test chamber.
- Implement updated models in EnergyPlus/UFAD (by LBNL).
- Update engineering documentation of EnergyPlus/UFAD (by LBNL).

The recommended activities in support of improving and refining the Cooling Airflow Design Tool include the following:

- To support the development and refinement of supplemental calculations and assumptions in the design tool, the improved version of EnergyPlus/UFAD will be used to conduct simulations of a prototype commercial office building. This will require the following work:
    - Develop a working EnergyPlus input model of a prototype office building with UFAD.
    - Conduct energy simulations with the prototype office building to evaluate the range of expected room load ratios defining the portion of the room cooling load assigned to the room and to the underfloor plenum.
- Add additional refinements and capabilities to the design tool, including:
    - Develop room load ratio for different building and plenum construction specifications.
    - Incorporate a factor to account for Category II room air leakage and provide guidance to users on what value to input to design tool.
    - If possible, include design guidance for a wider number of commercially available diffusers.
    - If possible, include design guidance for occupancy and room load distributions that differ from office buildings.
- Develop a suitable user interface for the spread-sheet based design tool.
- Use available field data collected through ongoing commissioning and energy use case studies to conduct a comparison and validation of the design tool.

4.3. Benefits to California

The newly developed EnergyPlus/UFAD is capable of conducting energy and demand sensitivity studies for a wide range of design, operating, and climate conditions. Awaiting the completion of this energy sensitivity study, the team has estimated the potential energy impact of UFAD technology on California as described below.

California—which is estimated to include about 10–15% of all national projects—likely offers greater potential for UFAD than do other areas of the country because of the state's mild climates, high use of raised floor systems, and high percentage of builder/designers inclined to be "early adopters." Industry sources indicate that UFAD is currently accounts for 50% of all California raised floor projects—a percentage that is growing—and that the rate of increase in raised floor projects in California is 1–2% greater than the rate of the overall construction.

To date, UFAD has seen greater application in the office building sector than other sectors. However, UFAD use is growing in public buildings, such as libraries, and has become more popular with commercial retail developers. Further, within the office sector, various subsectors are increasing UFAD use, including financial institutions, university administration and student centers, and credit card centers. Such trends are difficult to predict, much less to quantify. As an example of potential, the team estimated the HVAC energy savings for UFAD in one sector, large offices, over the next 10 years. For UFAD penetration, the team assumed that the growth rate would continue to reflect the rates since 1999, as well as the following:

- Overall new construction growth rate: 2% per year, constant
- Fan energy savings: 22%, based on a previous study of fan savings (Webster 2000)
- Economizer savings: 15% and 30%

The team ignored potential chiller savings, since data are lacking as to the magnitude and since the proportion of chilled water systems is less than 40% even in large buildings. Economizer savings of 30% are based on a model that uses Oakland weather data for a typical meteorological year; less benign climates are assumed to yield 15% savings.

New construction for the estimate includes both retrofit and new buildings, since the team's estimate for penetration is based on annual sales of raised floor panels with an unknown breakdown between the two. However, based on the CBE Case Studies project, the team estimates that 25% of new UFAD projects are retrofits to existing facilities. The teams used as the baseline (without escalation) the California commercial end-use energy use intensities for ventilation and cooling and the aggregate floor areas for large offices, as provided by PIER.

The values shown in Table 7represent the estimated potential energy savings expressed as a percent of the overall HVAC energy use for all new construction of large offices (based primarily on a building stock of conventional systems). As shown, UFAD could reduce energy use in new large office buildings by almost 25% in 2010 and more than 50% by 2015.

Table 7. Percent savings in HVAC energy for large office building new construction for given UFAD market penetrations

	% Energy Savings by Year		
	2005	**2010**	**2015**
UFAD projected penetration rates in large new offices	6%	24%	53%
% of HVAC energy with 15% economizer savings	1%	4%	10%
% of HVAC energy with 30% economizer savings	2%	6%	14%

Additional benefits to California based on the results of this project are listed below:

- Improve the effectiveness of building design and construction practices by providing validated energy simulation and design tools that optimizes the energy and cost effectiveness of UFAD systems.
- Help policymakers establish methodologies in future releases of Title-24 that allow proper receipt of credits on projects that implement UFAD in an energy-conserving manner by providing an updated and clearer picture of the potential energy use benefits of UFAD systems.
- Improve the health and safety of building occupants by establishing a database of test information that could be used to analyze thermal comfort of UFAD systems and assist with future studies of ventilation effectiveness.
- Increase customer choices for efficient operation of buildings by providing standardized design and analysis tools and technical knowledge that would reduce the risk to practitioners and owners when choosing to implement UFAD technology.
- Encourage the rapid incorporation of research findings into UFAD products by working closely with UFAD industry leaders, including York International, a partner on this project, and other major HVAC manufacturers who are members of CBE.

5.0 References

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6.0 Glossary

Acronym	Definition
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
Btu	British thermal unit
CBE	Center for the Built Environment
CFD	computational fluid dynamics
cm	centimeter
cfm	cubic feet per minute
DOE	U.S. Department of Energy
EC	environmental chamber
ft	foot
ft^2	foot square
HD	horizontal discharge
HVAC	heating, ventilating and air conditioning
IAQ	indoor air quality
IEQ	indoor environmental quality
IP	inch-pound
LBNL	Lawrence Berkeley National Laboratory
m	meter
m^2	meter squared
OH	overhead air
PAC	Project Advisory Committee for this PIER contract
PEC	Pacific Energy Center
PIER	Public Interest Energy Research
RAB	return air bypass
RAS	room air stratification
SAT	supply air temperature
UCB	University of California, Berkeley

UCSD	University of California, San Diego
UFAD	underfloor air distribution
VA	variable area
VAV	variable air volume
York	York International
W	watt

Appendices

Appendix A. Part II: Room Air Stratification Full Scale Testing	CEC-500-2007-XXX-APA
Appendix B. Part II: Laboratory Layouts and Normalization of Room Air Stratification Profiles	CEC-500-2007-XXX-APB
Appendix C. Part III: The Fluid Dynamics of a UFAD System	CEC-500-2007-XXX-APC
Appendix D. Part IV: Underfloor Plenum Testing and Modeling	CEC-500-2007-XXX-APD
Appendix E. Part V: EnergyPlus Development	CEC-500-2007-XXX-APE
Appendix F. Part VI: UFAD Cooling Airflow Design Tool	CEC-500-2007-XXX-APF