Modeling of Underfloor Air Distribution (UFAD) Systems

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Outline of presentation

- Project overview
- UFAD vs. overhead
- Development of room air stratification model
- Development of plenum model
- EnergyPlus system upgrades
- EnergyPlus validation
- Simulation results and examples
- Summary and next steps
Energy performance of UFAD systems

- **Objective**
  - Develop a version of the whole-building energy simulation program, EnergyPlus, capable of modeling UFAD systems

- **Project details**
  - Phase 1 – Project start: November 2002
  - Phase 1 – Final report: December 2006
  - Phase 2 – Ongoing, completion in December 2008
  - Primary funding from California Energy Commission (CEC) Public Interest Energy Research (PIER) program
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Basics: Overhead vs. UFAD

- 55 - 57°F SAT
- 60 - 65°F SAT
Key issue #1: Room air stratification (cooling operation)

- Cool and fresher air in the occupied zone
- Stratification created by thermal plumes
- Assumption of well-mixed conditions no longer valid
Key issue #2: Underfloor air supply plenums

- Airflow and pressure distribution in an open pressurized plenum is quite uniform
- Temperature distribution (thermal decay) is not
- Construction quality air leakage can be significant
Methodology overview

- **Objective:** Provide comprehensive modeling capability for UFAD systems in EPlus

- **Two major differences from traditional overhead (OH) systems**
  - Room air stratification (RAS)
    - Non-uniform room temperature
  - Underfloor air supply plenum
    - Thermal decay
    - Air leakage

- **Developmental approach**
  - Theoretical models
  - Bench scale testing
  - Full scale testing
  - Develop simplified EPlus models for RAS and supply plenums
UFAD theory – Interior zone

UCSD – See “The EnergyPlus UFAD Module” by A. Liu, P. Linden

Diagram showing heat sources and floor cooling diffuser.
Bench-scale tests – Interior zone

Floor heat source

Heat Source

Cooling Diffuser

Elevated heat source

Temperature (normalized)

Height

Measured

Model

UFAD 300: heat source on the floor

UFAD 302: heat source on 1/2H
Full-scale stratification testing

- Realistic office configurations
- Perimeter and interior zones
- 150 data points (suitable for heat balances)
UFAD diffuser types

Variable area (VA)

Swirl

Linear bar grille

Swirl, horizontal discharge (HD)
Full-scale results – Interior zones

- **Effect on stratification of diffuser type**
  - Using nominal diffuser design airflow, 3.5 W/sf internal load
Full scale results – interior zones

- Effect of diffuser throw height on stratification

Bench-scale experiments & theoretical model

Full-scale lab testing (Swirl diffusers)

Temperature (normalized) vs. Height

- 1 diffuser
- 2 diffusers
- 3 diffusers
- 8 diffusers
- 14 diffusers
- 6 diffusers
Full-scale results - Perimeter

- Impact of diffuser throw and blinds on stratification
  - Peak solar, perimeter zone load = 14.8 W/sf
  - Equivalent to West zone, July 21, 40° North, SHGC = 0.37, WWR = 0.74
Theory to practice

- **Analytical parameters for multiple plumes (m) and diffusers (n)**

  - Temperature effectiveness ($T_{eff}$), represents the degree of stratification
  
  \[
  T_{eff} = \frac{Toz - Ts}{(Tr - Ts)}
  \]

  Gamma ($\Gamma$) = ratio of momentum to buoyancy

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

  ($Q =$ total diffuser airflow, $A_{eff} =$ diffuser effective area, $W =$ load, plume strength, $\varphi =$ diffuser discharge angle, $n =$ # of diffusers, $m =$ # of plumes)
- Occupied zone (OZ, 4” to 67”) temperature effectiveness (T_eff) vs. Gamma

\[
T_{eff} = -0.0001x^2 + 0.0118x + 0.6531 \\
R^2 = 0.9381
\] (Swirl)

Average \( T_{eff} = 0.67 \) (HD)

Average \( T_{eff} = 0.88 \) (VA)
Development of RAS model for EnergyPlus

- Theoretical and experimental (small- and full-scale) studies allowed development of room air stratification (RAS) model.
- The simplified RAS model used in EnergyPlus divides the room into two well-mixed zones separated by a boundary that is transparent to radiant exchange.
- While oversimplifying real stratification, this scheme captures first order effects well and is simple enough for use in EnergyPlus.
Thermal performance of underfloor plenums

- **Key issues:**
  - Thermal decay with distance
  - Temperature distribution due to inlet configuration

- **Model development**
  - Create CFD model
  - Full-scale experiments
  - Validate CFD model vs. experiments
  - CFD simulations to study thermal performance for various design and operating conditions
  - Develop simplified plenum model for implementation in EnergyPlus
Comparison of CFD to experiments

Predicted diffuser temperature (°F)

Measured diffuser temperature (°F)

52.8°F supply air temperature
Development of plenum model for 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.

- Despite the complexity of the plenum airflow and heat transfer processes, the plenum energy balance predicted by the CFD model 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 plenum is modeled as a separate well-mixed zone with average surface convection coefficients (based on detailed CFD simulations) specified as a function of total plenum airflow rate.
Typical plenum configuration

Plenum inlet

Diffusers

INTERIOR

PERIMETER

Fan coil unit
EPlus supply plenum model

- Plenum air is assumed fully mixed
- Plenums in series to simulate thermal decay

\[ T_{\text{out}1}(T_{\text{plenum1}}) = T_{\text{in}2} \]

\[ T_{\text{out}} = T_{\text{plenum2}} \]
EPlus system upgrades: Variable speed fan coil

- Return Air Plenum
- Raised Access Floor
- Return Air Grille
- No U/A diffusers in perimeter zones
- Variable-speed fan coil
- Heating Coil
- Linear Bar Diffuser
- Flex Duct
- Glazing
EPlus system upgrades: Return air bypass
EnergyPlus – UFAD modeling summary

- Layered fully mixed zones
- 2-node room model using newly created **UFADManager**
  - Full heat balance on each layer
  - Boundary between zones is transparent to radiation heat transfer
- Semi-empirical stratification models for interior and perimeter zones
- Fully mixed supply plenum with custom convection coefficients
- System upgrades
  - Variable speed fan coil unit
  - Return air bypass at AHU
Validation - Test chamber model
Simulation validation – Temperature profile

- Interior zone, measured data vs. full scale test chamber simulation
- Closely simulates air and surface temperatures in room and supply plenum
Validation

- Root mean square error (RMSE) for surface and air temperature differences
  - 29 interior zone tests
  - Raised floor top temperature difference due mixed lower zone
Heat transfer pathways - Interior zone, middle floor

Distribution of total system heat gain

**From**
- Perimeter zone
- Supply Plenum = 48%
- Room = 61%
- Plenum Average = 65°F

**To**
- AHU
- Return plenum = -9%
- Gain from ceiling & lights = 4%
- Gain from floor = 26%
- Gain from slab = 22%
- Ceiling radiation (net) = 6%
- Floor radiation (net) = 31%

Loss to slab = -13%

Conditions: Room lower zone room temperature = 74°F, Airflow = 0.58 cfm/sf, Load = 3 W/sf, stratification ~ 3°F
We simulate a multi-story building by connecting the bottom of the supply plenum to the top of the return plenum.
UFAD Lab
Vertical Temperature Distribution

Return Air Temperature

Return Plenum

76.6

76.6

78.3

Calculated Data

Room

75.0

67.1

58.0

Supply Air Temperature

Supply Plenum

Temp [°F]
50 55 60 65 70 75 80 85 90

Cooling Distribution

Room, 60%

Supply Plenum, 49%

Return Plenum, 9%
Summary and next steps

- Phase 1 of EnergyPlus/UFAD development is complete
  - Validated RAS model for interior zones
  - Validated underfloor plenum model
  - UFAD system upgrades

- For copy of final report:
  “Energy Performance of UFAD Systems”
  www.cbe.berkeley.edu/research/briefs-ufadmodel.htm

- Phase 2 work is ongoing (December 2008)
  - RAS model for perimeter zones
  - EnergyPlus/UFAD simulations will compare energy and demand response performance of UFAD vs. overhead systems in a prototype large commercial office building
Questions?

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