BSE Public CPD Lecture – 
Numerical Simulation of Thermal Comfort and Contaminant Transport in Rooms with 
UFAD system on 26 March 2010

Organized by the Department of Building Services Engineering, a public CPD lecture delivered by Professor Yitung Chen on Numerical Simulation of Thermal Comfort and Contaminant Transport in Rooms with UFAD system was held on 26 March 2010 (Friday). 77 participants attended the lecture.

Powerpoint file of the CPD lecture

Professor Yitung Chen is a Professor of the University of Nevada Las Vegas (UNLV), as well as Co-Director of the Centre for Energy Research at UNLV. His main research interests include thermal-fluid science, computational fluid dynamics, nuclear energy, renewable energy, environmental engineering and fuel cell.
In the lecture, Professor Chen explained that it is important to analyze energy efficiency with thermal comfort for UFAD systems and reduce the design cycle through the development of mathematical and computational models. In this study, thermal comfort of occupants in 2-D and 3-D model of a room has been analyzed. The flow characteristics such as velocity, temperature, relative humidity and species concentration for both the models have been calculated.

Professor Chen presented his analysis with supporting data to show that the obtained results from the numerical study were reasonable.
Numerical Simulation of Thermal Comfort and Contaminant Transport in Rooms with UFAD System

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March 26, 2010
Outline

• Introduction
• Research objectives
• Focus of the study
• Numerical approach procedure
• Numerical modeling of UFAD system of a 2-D office setting
• Parametric study
• Numerical simulation of thermal comfort and CRE of UFAD system of BTLab
• Conclusions
Introduction

- Underfloor air distribution (UFAD) systems have become popular design alternative to conventional air distribution (CAD) such as overhead distribution systems for thermal and ventilation control
  - UFAD advantages
    - reduced life cycle building costs
    - improved thermal comfort
    - improved ventilation efficiency and indoor air quality (IAQ)
    - reduced energy use
    - improved productivity and health
- Resistance to wider use

Reference: www.cbe.berkeley.edu/.../techoverview.htm
Introduction (cont.)

- Swirl diffusers are designed to provide rapid mixing with the room air and thus minimize any high velocity air movement, except within clear zone.
- Clear zone:
  Approximately 4 ft high and 2 ft in diameter, directly above the floor diffuser.
  In the outside of clear zone, room air velocities will be less than 50 fpm.

The airflow patterns in a hybrid underfloor system (Loudermilk 1999)
Learning from Literature Reviews

• CFD models have been used in the study of thermal comfort, IAQ, contaminant distributions and design of HVAC systems
• The increasing developments of CFD in the recent years have opened the possibilities of low-cost yet effective method for improving HVAC systems in design phase, with less experimentation required
• Very little research studies have been done on UFAD systems in North America
• The most common turbulence model used is the two-equation model
Research Objectives

• To model and analyze the 2-D model of an office room by providing detailed and complete information regarding the velocity, temperature, relative humidity, and species concentration for benchmarking numerical approach procedures

• To study the thermal comfort and contaminant transport in UFAD system using 3-D model of BTLab located at UNLV from previous study

• To study the thermal comfort and the contaminant removal effectiveness (CRE) of a real-life 3-D model (with a human model and furniture) by studying the flow characteristics
Focus of the Study

• Thermal comfort modeling
• Modeling of contaminant species transport
Thermal Comfort

- Human thermal comfort is the state of mind that expresses satisfaction with the surrounding environment, according to ASHRAE Standard 55
- In terms of bodily sensations, thermal comfort is a sensation of hot, warm, slightly warmer, neutral, slightly cooler, cool and cold
  - Temperature
    - The range of temperature recommended is 18 - 23°C
    - The temperature difference in the occupied zone shouldn’t exceed 1°C
  - Relative humidity
    - The relative humidity levels recommended by different organizations ranges from 30-60%
    - The relative humidity greater than 70% causes discomfort to the occupants
  - Velocity
    - Air velocity that exceeds 40 feet per minute or 0.2032 meter per second, or cool temperatures combined with any air movement, may cause discomfort
Predicted Mean Vote (PMV)

- It is a parameter for assessing thermal comfort in an occupied zone based on the conditions of metabolic rate, clothing, air speed besides temperature and humidity.

\[
PMV = f(M, W, p_w, T_a, T_{cl}, f_{cl}, h_c) \quad \text{(Fanger Model)}
\]

where

- \( f_{cl} \): Ratio of clothed surface area
- \( M \): Metabolic heat generation flux, \( W/m^2 \) of naked body area
- \( W \): External work, \( W/m^2 \) of naked body area
- \( T_a \): Mean temperature of air
- \( T_{cl} \): Mean temperature of clothing
- \( h \): Heat transfer coefficient, \( W/(m^2\cdot k) \)
- \( p_w \): Partial pressure of water vapor, Pa

Thermal Sensation Index (Y)

• The empirical equation for men and women combined with exposure period of 3 hours, conversed for SI units, is given by

\[ Y = 0.243 \, T_a + 0.000278 \, p_w - 6.802 \]

• ASHRAE thermal sensation scale ranges from -3 to 3 as follows:
  3=hot, 2=warm, 1=slightly warm, 
  0 = neutral, 
  -1=slightly cool, -2=cool, -3= cold
Contaminant Removal Effectiveness (CRE)

\[
CRE = \frac{C_E - C_S}{C_{BZ} - C_S}
\]

where

- \(C_E\) : the mean concentration in exhaust
- \(C_S\) : the mean concentration in supply air
- \(C_{BZ}\) : the mean concentration in occupied zone

if \(C_S = 0\), then

\[
CRE = \frac{C_E}{C_{BZ}}
\]
Numerical Approach Procedure

Governing Equations:

• The governing time-averaged partial differential equations for conservation of mass, momentum, and energy are:
  - Continuity equation:
    \[ \frac{\partial \rho U_j}{\partial x_j} = 0 \]
  - Momentum equation:
    \[ \frac{\partial}{\partial x_j} \left( \rho U_i U_j \right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho u'_i u'_j \right] - \rho g_i \]
  - Energy equation:
    \[ \frac{\partial}{\partial x_j} \left( \rho U_j C_p T \right) = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} - \rho u'_j T' \right) \]
Governing Equations (Cont.)

The turbulent stress and heat flux are determined by

\[ \rho u'_i u'_j = \mu_t \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho \delta_{ij} k \]

\[ \rho u'_i T' = \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \]

where \( \mu_t = \frac{\rho C_{\mu} k^2}{\varepsilon} \)

where \( \rho \) : density (kg/m\(^3\))

\( \mu \) : dynamic viscosity (kg/m-s)

\( \mu_t \) : turbulent viscosity (kg/m-s)

\( P \) : pressure (Pa)

\( C_p \) : specific heat capacity (J/kg-K)

\( \lambda \) : thermal conductivity (W/m-K)

\( g_i \) : gravitational constant (m/s\(^2\))

\( \delta_{ij} \) : kronecker delta

\( T \) : temperature (K)
Governing Equations (Cont.)

The turbulence kinetic energy, \( k \), and its rate of dissipation, \( \varepsilon \), are obtained from the following transport equations

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k U_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon + S_k
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon U_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon
\]

where \( G_k = -\rho u_i' u_j' \frac{\partial U_j}{\partial x_i} \); \( G_b = \beta g_i \frac{\mu_t}{\Pr} \frac{\partial T}{\partial x_i} \) and \( \beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right) \)

where \( G_k \): generation of turbulent kinetic energy due to mean velocity gradients
\( G_b \): generation of turbulent kinetic energy due to buoyancy
\( C_{1\varepsilon}, C_{2\varepsilon}, \text{ and } C_{3\varepsilon} \): constants.
\( \sigma_k \) and \( \sigma_\varepsilon \): the turbulent Prandtl numbers for \( k \) and \( \varepsilon \)
\( S_k \) and \( S_\varepsilon \): user-defined source terms
\( \beta \): the coefficient of thermal expansion (1/K)
Governing Equations (Cont.)

The equations for the mass conservation of water vapor and contaminant gas are

\[
\frac{\partial}{\partial x_j} \left( \rho u_j \phi_k \right) = \frac{\partial}{\partial x_j} \left( D_k \frac{\partial \phi_k}{\partial x_j} \right)
\]

where \( \phi_k \) : water vapor or contaminant gas

\( D_k \) : the diffusion coefficient for \( k \) scalar

\( \phi_k \) : the mass diffusivity of species in air
Governing Equations (Cont.)

• The relative humidity can be computed by

$$\gamma = \frac{p_w}{p_{wsT}}$$

where

$$p_{wsT} = 1000 \exp\left(-\frac{5800}{T} - 5.516 - 0.04864T + 4.176 \times 10^{-5} T^2 - 1.445 \times 10^{-8} T^3 + 6.546 \ln T\right)$$

$$p_w = \frac{(101325 + p) \cdot m_{\text{watervapor}}}{0.62198 + 0.37802 \cdot m_{\text{watervapor}}}$$

where

- $p_w$ : actual vapor pressure
- $p_{wsT}$ : the saturated vapor pressure
- $T$ : mean temperature (K)
- $m_{\text{watervapor}}$ : the concentration of water vapor

Numerical Approach

- FLUENT is a computational fluid dynamics (CFD) software package to simulate fluid flow problems. Geometry and grid generation is done using GAMBIT which is bundled with FLUENT.

- A non-staggered grid storage scheme is adapted to define the discrete control volumes and the solver used is a segregated solver. The governing equations, discrete and nonlinear, are linearized using an implicit technique.

- The semi-implicit method for pressure-linked equations (SIMPLE) algorithm is used to resolve the coupling between pressure and velocity.

- FLUENT uses a control-volume-based technique to convert the governing equations to algebraic equations that can be solved numerically and the discretization method used is the finite volume method (FVM).
Numerical Modeling of UFAD System of a 2-D Office Setting

Schematic of typical 2-D cubicle in an office
Mesh Independent Study

To find the mesh independent solutions for this problem, three different mesh sizes were tested.

(a) Mesh independent study of velocity at inlet along the height of the cubicle and (b) mesh independent study of velocity at Y=1.8288 m across the width of the cubicle.
Mesh Independent Study (Cont.)

(a) Mesh independent study of temperature at inlet along the height and (b) mesh independent study of temperature at Y=1.8288 m across the width of the cubicle.
Mesh Independent Study (Cont.)

Optimized mesh of 27,330 quadrilateral cells were found and used to model the cubicle.

Number of cells: 27,330
Number of nodes: 28,102

Mesh system for the 2-D simulation of an office setting
Thermal Comfort and CRE Analysis on the 2-D Cubicle Office Setting

Boundary conditions:

- The supply air mass flow rate from each diffuser is 0.06 kg/sec contaminant free air
- The inlet air temperature, $T_{\text{inlet}} = 293.76$ K
- Human body temperature, $T_{\text{human}} = 306$ K
- Computer heat flux is 100 W/m$^2$
- Water vapor loss on the human body is 5e-7 kg/m$^2$-s
- Contaminant flux is taken as 1e-6 kg/m$^2$-s

Diffusivity of water vapor is 2.544e-5 m$^2$/s
Diffusivity of contaminant species is 2.503e-5 m$^2$/s

Numerical Simulation Results

Velocity vectors of the fluid flow

Velocity magnitude (m/sec)

X (m)

0.1 m/sec
(a) Water vapor concentration distribution, (b) Relative humidity distribution, and (c) Velocity distribution.

(kg/kg air)
(a) Temperature distribution

(b) Species concentration distribution
Vertical distribution of (a) average temperature, (b) average relative humidity, (c) average velocity, and (d) average species concentration.
Parametric study

Same mass flow rate on both diffusers

(a) Variation of temperature with mass flow rates
(b) Variation of relative humidity with mass flow rates
Parametric Study (Cont.)

Same mass flow rate on both diffusers

(a) Variation of PMV with mass flow rate
(b) Variation of Y with mass flow rate
Parametric Study (Cont.)

Different mass flow rates on diffusers

(a) Velocity magnitude distribution for different mass flow rate (0.1 kg/sec)

(b) Velocity magnitude distribution for different mass flow rate (0.03 kg/sec)
Parametric Study (Cont.)

Different mass flow rates on diffusers

(a) Variation of temperature with different mass flow rates
(b) Variation of relative humidity with different mass flow rates
Parametric Study (Cont.)

Different mass flow rates on diffusers

(a) Variation of PMV with different mass flow rates
(b) Variation of Y with different mass flow rates
BTLab at UNLV

Ductwork and AHU boxes in the ceiling plenum

Traversing mechanism and sensors’ pole

The underfloor plenum

Top view of the UFAD access floor

Data acquisition board
Numerical Simulation of Thermal Comfort and CRE of UFAD System of BTLab

Schematic of the domain for test space of BTLab with UFAD system
Thermal Comfort Analysis on the UFAD System of BTLab

(a) Grid system and computational domain of the UFAD system

(b) Zoom view of the swirl diffuser

- 4,440,050 cells are used for the whole domain
- Domain extents:
  - x-coordinate: min (m) = 0.000000e+000, max (m) = 9.144000e+000
  - y-coordinate: min (m) = -6.096000e+000, max (m) = 0.000000e+000
  - z-coordinate: min (m) = -1.100054e-001, max (m) = 2.743200e+000
Boundary Conditions

• Mass flow rate from each of the 8 swirl diffusers is 0.016834 kg/s
• The supply air temperature is set at 291.3 K
• The ambient air temperature is given as 300 K
• The underfloor is treated as adiabatic boundary conditions
• East wall temperature = 297.7 K
• West wall temperature = 297.6 K
• North wall temperature = 297.7 K
• South wall temperature = 297.3 K
• Ceiling temperature = 297.8 K
• Contaminant flux is taken as 1e-6 kg/m² -s

The mass diffusivity of water vapor and contaminant species are taken as 2.544e-5 m²/s and 2.503e-5 m²/s
Numerical Simulation Results

(a) whole view

(b) zoom view

Velocity vectors at a selected slice of $Y = -4.59$ m
Numerical Simulation Results (Cont.)

Velocity magnitude at a selected slice of $Y = -4.59 \text{ m}$
The clear zone is approximately 0.6m high and 0.8 m in diameter

(a) Temperature distribution at a selected slice of $Y = -4.59$ m
(b) Relative humidity distribution at a selected slice of $Y = -4.59$ m
Species concentration at a selected slice of $Y = -3.38\ m$
Numerical Simulation Results (Cont.)

(a) Vertical distribution of average temperature
(b) Vertical distribution of average relative humidity
Numerical Simulation Results (Cont.)

• The thermal sensation index ($Y$) is calculated to be -0.5 (in comfort zone)
• The predicted mean vote (PMV) is calculated to be -0.8 (in comfort zone)
• The contaminant removal effectiveness (CRE) is 1.01716
Numerical Modeling of Thermal Comfort and CRE of UFAD System with Swirl Diffusers in a Living Room

The model and mesh are generated in Gambit. 2,373,843 tetrahedron cells were used to simulate the fluid flow and heat transfer in the living room.

Schematic diagram of living room
Boundary Conditions

- The mass flow rate for each swirl diffuser is 0.076 kg/s contaminant-free air
- The temperature of supply air is 291 K
- Temperature of human body is 306 K
- Water vapor loss on the human body is $5 \times 10^{-7}$ kg/m$^2$-s
- Contaminant flux is taken as $1 \times 10^{-6}$ kg/m$^2$-s

Diffusivity of water vapor is $2.544 \times 10^{-5}$ m$^2$/s

Diffusivity of contaminant species is $2.503 \times 10^{-5}$ m$^2$/s

- Domain extents:
  - X-coordinate: min (m) = $-1.800000 \times 10^0$, max (m) = $6.600000 \times 10^0$
  - Y-coordinate: min (m) = $-3.660000 \times 10^0$, max (m) = $1.740000 \times 10^0$
  - Z-coordinate: min (m) = $-1.100000 \times 10^{-1}$, max (m) = $3.000000 \times 10^0$
Numerical Simulation Results

(a) Velocity vectors of the fluid flow at a selected slice of $Y = 0.604$ m
(b) Zoom view of the velocity vectors of swirl diffuser
Numerical Simulation Results (Cont.)

Pathlines released from swirl diffusers
Numerical Simulation Results (Cont.)

Velocity distribution (m/sec)
Numerical Simulation Results (Cont.)

Contaminant distribution (kg/kg air)
Numerical Simulation Results (Cont.)

Species concentration at a selected slice of $Y = 0.6366$ m
Numerical Simulation Results (Cont.)

(a) Average temperature distribution along height
(b) Average species concentration along height
Numerical Simulation Results (Cont.)

• The thermal sensation index (Y) is calculated to be -1.0 (slightly cool)
• The predicted mean vote (PMV) is calculated to be -1.0 (slightly cool)
• The contaminant removal effectiveness (CRE) is calculated to be 1.304
Conclusions

• In the numerical study of the 2-D office cubicle setting, the results satisfy the ASHRAE standards. Constant mass flow rate from both the diffusers is suggested.

• From the numerical study of the BTLab at UNLV, it has been observed from the velocity and temperature profiles that the flow inside the test space is well mixed. Flow characteristics and thermal comfort factors are in good agreement with the ASHRAE standards.

• The CRE was found to be good enough to vent most of the contaminants out of the room in spite of the floor obstructions. Hence, the positioning of the diffusers is fairly good to remove contaminants from the room.
Acknowledgement

This research is financially supported by the U.S. Department of Energy under grant DE-FC26-03GO13072