THE ENERGYPLUS UFAD MODULE

Qing A. Liu[1], and Paul F. Linden[2]

[1]Ove Arup & Partners, San Francisco, U.S.A
[2]University of California, San Diego, U.S.A

ABSTRACT

This paper discusses the development of an Underfloor Air Distribution (UFAD) interior zone model that has been implemented in EnergyPlus UFAD module for energy simulation. The theory of this UFAD module is based on the understanding of the fluid dynamics of UFAD systems (Liu and Linden 2006) and the qualitative and quantitative comparisons between small-scale laboratory experiments and full-scale room tests, both of which are described in this paper. The comparisons show that a two-zone stratification forms at steady state. For multiple-diffuser cases, the same trends of the stratification profiles were found in experiments with both scales. Non-dimensional parameters Γ and ϕ were defined to describe the inputs of the system and the resulting stratification of the space, respectively. The data from the laboratory experiments and the test room fall on a unique relationship of Γ and ϕ, which determines the room stratification. It is these equations that have been implemented in EnergyPlus UFAD simulation module.

KEYWORDS

UFAD, EnergyPlus, Small scale, Full scale, comparisons

INTRODUCTION

For a given supply temperature, the minimum flow rate occurs for the maximum return temperature (Liu 2006). Therefore, a system that produces stratification provides the potential for removing the heat load at a lower ventilation rate, thereby being energy efficient. Underfloor air distribution is one of these systems to allow the air within the space to stratify. UFAD is a novel ventilation strategy that utilizes raised-access floors serving as plenums to provide supply air into the lower zone where occupants are located. Individuals exposed to significant temperature variations over their bodies experience discomfort, as found in displacement ventilation systems. Therefore, the optimal operation of a UFAD system involves a delicate balance between the stratification needed for energy efficiency while retaining thermal comfort. However, engineers and designers lack information and

experience to design UFAD systems because the technology is in its infancy, and standardized methods and guidelines are still under development. The UFAD design guide by Bauman (2004) is the first and the only design book so far. Furthermore, designers need tools with which they can calculate the potential energy savings of a UFAD system when it is installed in a building. For conventional systems these calculations are made by running a thermal simulation program. These programs assume that each space within a building is well mixed and calculate the heat balances within each individual space, characterized by a single temperature, due to convective, conductive and radiative exchanges with the surfaces in the space. Since energy-efficient systems require stratification, these programs are unable to capture the energy savings. Thus there is a need to extend these simulation programs to include stratification. EnergyPlus, one of those programs, is a free and publicly available program maintained by the U.S. Department of Energy. Typically, it is run for whole buildings with a full "typical meteorologically year" of hourly weather data, and a simulation time step of 10 minutes. Consequently, the inclusion of stratification must be simple or the computational overhead will be too large.

One goal of this research is to develop UFAD models that can be implemented in EnergyPlus, in order to allow design practitioners to model the energy performance of UFAD systems and to compare them with that of conventional systems. Since radiation and other heat transfer mechanisms with the surfaces in a space are readily calculated, the key here is to model the flow and stratification in the space driven by the internal gains and the ventilation flow itself. Based on a solid understanding of the fluid mechanics of UFAD systems and numerous experiments, this EnergyPlus UFAD module will be the first comprehensive simulation program capable of modeling the energy performance of UFAD systems and comparing it with that of conventional systems.

Our approach is to develop algorithms that can be directly included into energy simulation codes. These algorithms are derived from models of the fluid flow that occur in buildings, which are, in turn, discovered using analogue laboratory experiments. While there are limitations in this approach as well, as we will discuss below, the fact that we are modeling observed flows provides a basis for knowing what essential

physics are captured, and what are not. Further, this approach leads to simplified design rules, since the physics is encapsulated in relatively simple formulas.

EXPERIMENTS

Laboratory experiments

The salt-bath technique used in this research has been used in buoyancy-driven flows for half a century, since Batchelor first used it to study the heat convection and buoyancy effects in fluids in 1954. Salt solution has a negative buoyancy force in fresh water, which is in contrast to the heat convection problems in building ventilation. However, for Boussinesq flows, this reversal of the direction of the buoyancy force is unimportant to the dynamics. If salt solution is introduced through a source nozzle at the top of a tank of fresh water, a plume forms in the tank. On the contrary, if fresh water is injected downward into a tank of salt solution, a fountain forms (Lin 2003).
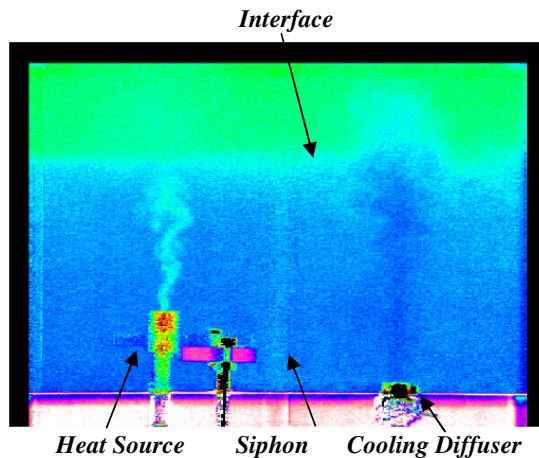

Figure 1 A false color image of the experiment with an elevated heat source and one cooling diffuser. The image has been inverted to represent the orientation appropriate to building ventilation.

Experiments were conducted in two, clear rectangular plexiglas tanks (tank #A with cross sectional area 30.6 cm ×15.3 cm and 30.6 cm deep, and tank #B with the dimensions of 58.5 cm long, 28 cm wide and 58.5 cm deep) filled with fresh water. A plume whose source is vertically adjustable and one or two cooling diffusers are set up on a mount immersed in the tank. The circular plume nozzle (diameter = 0.5cm) used in the experiments was designed by Dr. Paul Cooper in the Department of Engineering, University of Wollongong, NSW, Australia. This design has a sharp expansion which excites a turbulent flow and, therefore, a turbulent plume is produced at the point of discharge. The cooling vent sources in the experiments are plexiglas pipes (1.27cm inner diameter) with a piece of fine mesh (aperture size about $0.1cm \times 0.1cm$) wrapped over one end to

produce turbulent fountains. A siphon pipe with an inner diameter 1.57cm was used to ensure a constant volume of fluid in the tank.

Since food coloring has a similar diffusion coefficient as salt, the dye acts as a tracer for density. Light intensity signals were used to measure the density distribution and investigate the flow pattern evolution.

All experiments were recorded by capturing images with a 4910 series monochrome CCD camera at one-minute intervals through a DT-2862 60Hz frame grabber card into a computer hard drive. Tracing paper was used between the lighting source and the water tank to diffuse the light to make it as uniform as possible. The mean light intensity across the width of the tank under a constant lighting source was analyzed by visualization software, DigImage (Dalziel 1993).

Full-scale Room Tests

The full-scale room air stratification tests were carried out in a 63 m^2 test chamber with a height of 2.7 m by the Center for the Built Environment (CBE) at the University of California, Berkeley (Figure 2).
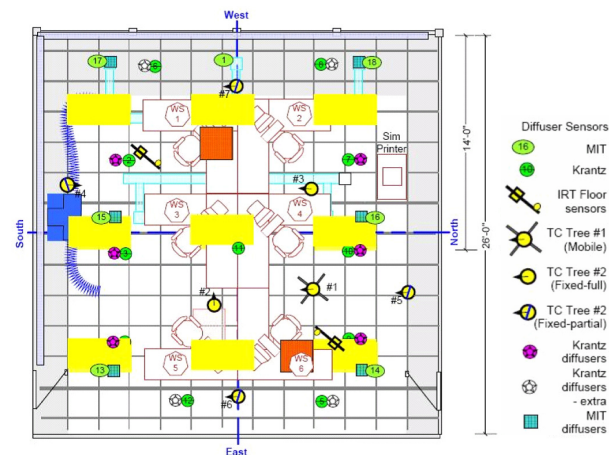

Figure 2 The full-scale chamber layout

Temperature sensors, thermal manikins, personal computers, desk lamps and other equipment were placed in the room to simulate typical office arrangements. Interior spaces were simulated by putting foam insulating panels on the west window wall and over the windows on the south wall of the test chamber.

There are 6 workstations in the test room. Each workstation consists of a thermal manikin, a personal computer and a desk lamp. Four different types of diffusers were used: standard swirl (up to 16 in total in the room), horizontal-discharge swirl (up to 14), Modular Integrated Terminal (MIT) (up to 10), and linear bar grille (up to 10 in perimeter zone only). In order to measure the vertical temperature distribution, thermocouples were installed at different heights on a

mast to form a so-called "thermocouple tree". This mast was clamped between the ceiling and the floor. All room temperature profiles in the following comparisons are the average measurements from 7 thermocouple trees (Webster et al. 2006).

RESULTS ANALYSIS

Qualitative Comparisons

Liu and Linden (2006) discussed the effects of multiple diffusers for a UFAD system. Both their theoretical model and the salt-tank experiments show that when the total ventilation flow rate is held fixed, the interface height decreases with a bigger number of diffusers per heat source n', approaching the displacement limit at large n'; and the buoyancy difference increases to the same limit for large n'.

The measurements for three experiments listed in Table 1 are shown in Figure 3(a).

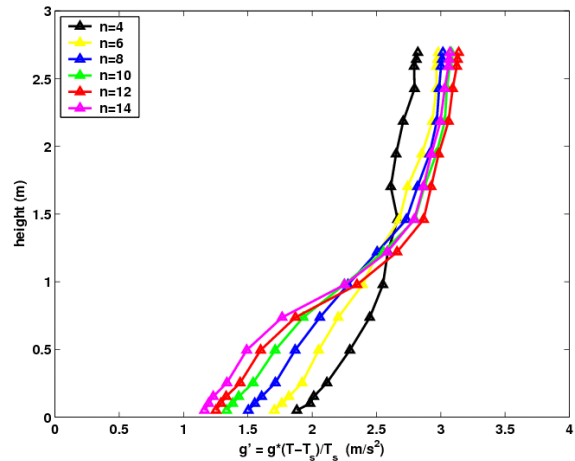*Table 1 Small-scale multi-diffuser experiments*

Exp. ID	B cm⁴s⁻³	M cm⁴s⁻²	Q cm³s⁻¹	n'	Tank #
1	69.3	182	15.2	1	A
2	68.2	45	7.6	2	A
3	70.1	26	5	3	B

Table 2 Full-scale multi-diffuser (swirl diffuser) tests

Test ID	W kW	Q m³s⁻¹	Ts K	n'	Γ
F1	2.27	0.181	292	0.67	18.62
F2	2.29	0.183	292	1	11.30
F3	2.31	0.194	291	1.33	8.60
F4	2.30	0.182	291	1.67	5.92
F5	2.25	0.178	292	2	4.62
F6	2.26	0.189	292	2.33	4.15
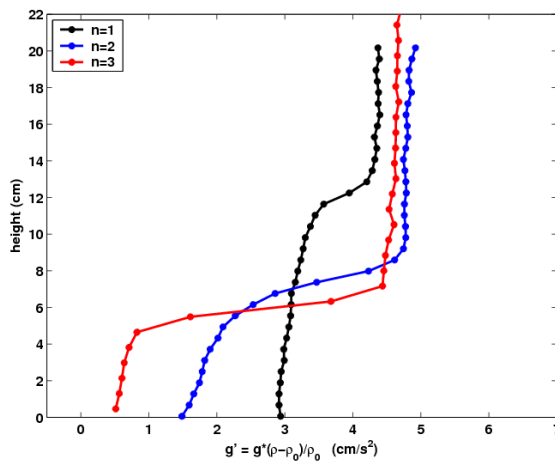
(a) small-scale experiments

(b) full-scale room tests
Figure 3 Stratifications of multiple-diffuser study with fixed total heat load and total room ventilation rate

Figure 3(b) demonstrates 6 real UFAD room test runs (Table 2) using swirl diffusers with the same heat load and ventilation flow rate, but different numbers of swirl diffusers (varying from 4 to 14). The same trends were found when more diffusers are used, i.e. the upper layer temperature T_r remains the same, but the temperature profile gets more stratified and the interface height decreases with larger number of diffusers.

Quantitative Comparisons

In order to determine whether the scaling of the laboratory tank experiments matches that of the room chamber tests, we examine non-dimensional scaling comparisons in this section.

Lin and Linden (2005) showed that in a UFAD system, the buoyancy flux of the heat source B and the momentum flux of the cooling jets M are the controlling parameters on the stratification. Therefore, a non-dimensional parameter Γ can be defined from B, M and the effective area of a diffuser A_d as

$$\Gamma = \frac{M^{3/4}}{A_d^{1/2}B^{1/2}} = \frac{Q^{3/2}}{A_d^{5/4}B^{1/2}}. \quad (1)$$

Physically, Γ represents the competition between stratification and mixing, because B is the source to build up the stratification while M measures the mixing of the diffusers. For the same geometry of the diffusers, large Γ means that the mixing dominates, and for small Γ we expect more stratification in the space.

Practically, Γ is a parameter based only on external variables: B, Q and A_d. Therefore, it does not

require the geometry of the space or internal measurements, which is a big advantage from the viewpoint of design and simulation.

For multi-diffuser and multi-source cases, the idea of dividing the whole enclosure into sub-regions with equal number of diffusers and single heat source in each sub-region is applied. The air flow and the heat load into each sub-region Q' and B' will be $Q' = Q/m$ and $B' = B/m$ respectively, where m is the number of heat sources, Q and B are the total air flow and the total heat load for the entire UFAD space. Then the momentum flux each diffuser per heat source carries is

$$M_d = (\frac{1}{n'}Q')^2 / A_d . \quad (2)$$

Therefore, (1) will be modified as

$$\Gamma = \frac{Q^{3/2}}{m(n'A_d)^{5/4}B^{1/2}} . \quad (3)$$

In a real full-scale room, the total room net heat load (plume heat input, minus the room losses) and the total net flow rate coming from the diffusers (input room air flow, minus the room leakage) should be considered. Further, diffusers flow rises until the vertical momentum reduces to zero, after which it reverses and falls towards the floor. Therefore, the vertical component of momentum flux should be used.

$$\Gamma = \frac{(Q\cos\theta)^{3/2}}{m(n'A_d)^{5/4}(0.0281W)^{1/2}} , \quad (4)$$

where the unit conversion from buoyancy flux to heat flux W has been applied.

The second dimensionless parameter - the ventilation effectiveness ϕ, which indicates the strength of stratification, is defined as

$$\phi = \frac{\rho_u - \rho_l}{\rho_u - \rho_o} , \quad (5)$$

Where ρ_u and ρ_l are fluid density of the upper layer and lower layer, respectively and ρ_o is the reference density. Equivalently, in terms of temperature

$$\phi = \frac{T_r - T_{oz}}{T_r - T_s} , \quad (6)$$

where T_r, T_{oz} and T_s (K) are the return air temperature, the occupied zone temperature and the supply temperature, respectively.

The maximum stratification corresponds to $\phi = 1$ (displacement ventilation case), while $\phi = 0$ implies that there is no stratification (well-mixed ventilation case).

Interior zone scaling comparisons

Figures 4 and 5 show the small-scale and full-scale experimental data in the Γ - ϕ plot. The salt tank experiments include single-plume single-diffuser cases (with plume on or above the floor) and multiple-plume multiple-diffuser ones. The selected room chamber tests include heat sources as manikins, printers and workstations.

The number of swirl diffusers varies from 2 to 12. As seen in figure 4, the experimental data collapse on the same line in the log-log Γ - ϕ plot, which provides evidence that our salt tank experiments have included most of characteristics of a UFAD system and that the scalings match with that of room chamber tests. The least squares best-fit line y=-0.76x+0.47 shows that, as expected, ϕ decreases as Γ increases, since larger Γ means more mixing and less stratification. The least-squares fit in figure 4 allows us to calculate the occupied zone temperature from knowledge of the diffuser design, the ventilation flow rate, the heat load and the supply temperature.
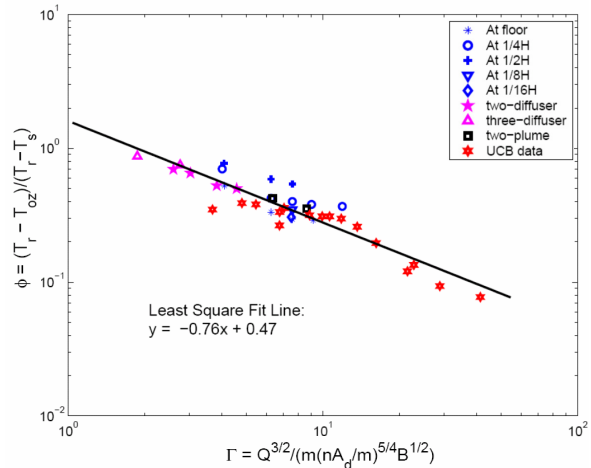

Figure 4 Data comparisons in the non-dimensional regular Γ - ϕ plot.
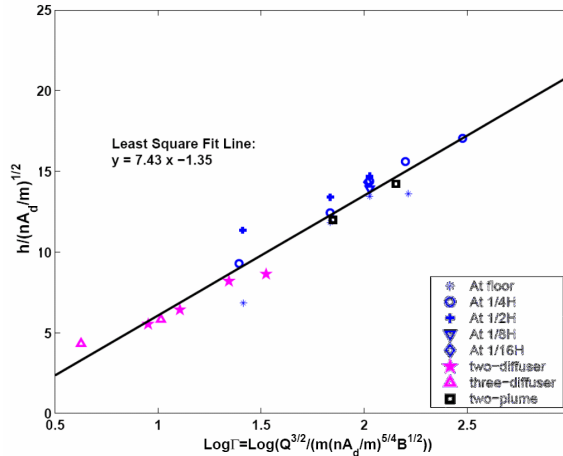
Figure 5 Non-dimensional interface height of small-scale experiments.

In order to complete the description of the stratification, the interface height is needed. Figure 5 shows the dimensionless interface height $\hat{h}_i = h/\sqrt{n'A_d}$ of our small-scale experiments plotted against Γ. Based on the discussion in Liu and Linden (2006), the effect of an elevated heat source is to produce a linear increase in the interface height by approximately one-half the height of the heat source. Therefore, for the experiments with elevated heat source, the interface heights have been modified by (7).

$$h' = h - \frac{1}{2}h_s. \quad (7)$$

All data then are located along a line y=7.43x-1.35 in figure 5.

From Liu and Linden (2006), the return air temperature

$$T_r = \frac{0.0281W}{Qg}T_s + T_s. \quad (8)$$

Therefore, the occupied zone temperature

$$T_{oz} = T_r - 1.6\Gamma^{-0.76}(T_r - T_s), \quad (9)$$

and the interface height h

$$h = \sqrt{\frac{n}{m}}A_d[7.34In(\Gamma) - 1.35] + \frac{1}{2}h_s. \quad (10)$$

Now, we go back to figure 3 to compare scalings between the two figures. The three laboratory experiments in figure 3(a) and six chamber tests in figure 3(b) are included in figure 4. Therefore, the stratification scalings among those experiments are matching. In the room tests a clear interface height is hard to determine, because the temperature profile is relatively smooth (figure 3(b)). Consequently, the interface data of room tests are not included in figure 5. However, based on the values of Γ given in table 2, the interface heights of these tests are estimated to range from 1.01 to 1.29 m by equation (10), with a proper virtual origin of the convective heater assumed (Liu 2006). This interface scaling is consistent with the stratification profiles shown in figure 3(b). Hence, the interface scalings of the chamber tests also match with our salt tank experiments.

EnergyPlus implementation

EnergyPlus requires straightforward inputs and outputs. We have shown that the scalings of small-scale experiments match full-scale experiments. Therefore, from the scaling comparisons, explicit equations are obtained for interior zone stratification (equation (8)-(10)). These equations have been implemented into EnergyPlus, and have provided reasonable estimates for room stratifications, thus providing guidelines for UFAD design purpose.

CONCLUSION

Both full-scale room testing data and small-scale experimental measurements collapse on a single line in Γ - ϕ figure. This fitting line verifies that the scalings are matching, and further, it provides the temperature in both layers for given values of Γ. We also obtain a Γ - $\hat{h}_i$ plot based on the small-scale experimental data, where $\hat{h}_i$ is the non-dimensional interface height. The correlation gives practical estimates for the interface height position in a real UFAD room. This provides the basis of the theory implemented in EnergyPlus UFAD module.

Although only some of the simplest tests were chosen to compare with our laboratory experiments, the UFAD module provides reasonable estimate for the stratification in a UFAD interior zone.

NOMENCLATURE

A_d effective area of each diffuser, m^2

B buoyancy flux from a single heat source, m^4/s^3

B' total heat load for each sub-region with a single heat source n' number of diffusers per heat source

g gravitational acceleration, m/s^2

h_s vertical position of the elevated heat source in each sub-region, m.

$\hat{h}_i$ non-dimensional interface height

m number of heat sources

M momentum flux out of all diffusers, m^4/s^2

Q net flow rate coming out from all diffusers, m^3/s

Q' net flow rate for each sub-region with a single heat source, m^3/s

T_r return air temperature, K

T_s supply temperature, K

T_{oz} occupied zone temperature, K

W total net heat load, kW

θ angle of the diffuser slots from vertical, degree

ρ_l density of the lower layer, g/cm^3

ρ_o reference density (fresh water), g/cm^3

ρ_u fluid density of the upper layer, g/cm^3

ϕ ventilation effectiveness

Γ dimensionless parameter represents the competition between mixing and stratification

ACKNOWLEDGMENT

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