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Authors

Schiavon, Stefano
Webster, Tom
Dickerhoff, Darryl
et al.

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Stratification prediction model for perimeter zone UFAD diffusers based on laboratory testing with solar simulator

Stefano Schiavon^{a*}, Tom Webster^a, Darryl Dickerhoff^{a,b}, Fred Bauman^a

^a Center for the Built Environment, University of California, Berkeley, CA 94720, USA

^b Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

* Corresponding author at: Center for the Built Environment, University of California, 390 Wurster Hall, Berkeley, CA 94720-1839, USA, Tel +1 510 859 3811

E-mail: stefanoschiavon@berkeley.edu

ABSTRACT

Underfloor air distribution (UFAD) is an innovative air distribution strategy for providing ventilation and space conditioning in buildings. UFAD systems use the underfloor plenum beneath a raised floor to provide conditioned air through floor diffusers that creates a vertical thermal stratification under cooling operation. Thermal stratification affects energy, indoor air quality and thermal comfort performance.

The purpose of this study was to characterize the influence of linear bar grilles and VAV directional diffusers on thermal stratification in perimeter zones by developing theoretically and empirically based models. Forty seven laboratory experiments were carried out in a climatic chamber equipped with a solar simulator.

Linear bar grilles tend to produce less stratification than VAV directional diffusers and, in some cases with high airflow rates, may generate reverse stratification. Lowering internal blinds causes an increase in thermal stratification. Models to predict temperature stratification for the two tested diffusers have been developed.

KEYWORDS

Underfloor Air Distribution (UFAD); Air temperature stratification; Diffuser; Ventilation; Thermal comfort

INTRODUCTION

Underfloor air distribution (UFAD) is an innovative method of providing space conditioning and ventilation to buildings. UFAD systems use an underfloor supply plenum located between the structural concrete slab and a raised access floor system to supply conditioned air through floor diffusers directly into the occupied zone (ASHRAE 2013). UFAD systems have several potential advantages over traditional overhead systems, such as layout flexibility, improved air quality, personal control, and energy efficiency (in suitable climates), and reduced life cycle costs (ASHRAE 2013). Their performance has been investigated through field study investigations (Webster 2008a), full and bench-scale laboratory testing (Bauman 2007a; Liu and Linden 2008; Liu and Linden 2006), computational fluid dynamics (CFD) and analytical modelling (Pasut 2011), and whole-building energy simulation (RW.ERROR - Unable to find reference:1645; RW.ERROR - Unable to find reference:1878; Bauman 2010; Liu and Linden 2008; Raftery 2012; Webster 2010; Webster 2008b).

Properly controlled UFAD systems under cooling operation produce temperature stratification in the conditioned space resulting in 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. Under these conditions, the temperature at the ceiling can no longer be assumed to be equal to

the room setpoint temperature. Stratification affects energy performance, indoor air quality and thermal comfort (ASHRAE 2013).

Local and whole-body discomfort sensation are slightly affected by thermal gradient, but are strongly affected by average operative temperature (Wyon and Sandberg 1996). To better describe the thermal stratification, a dimensionless temperature, Φ (Phi), at a height in the room, is generally defined by the following equation:

$$\Phi = \frac{T - T_s}{T_r - T_s} \quad (1)$$

where T , T_s , and T_r , are the point, supply, and return air temperatures, respectively. The dimensionless temperature ratio at ankle level (0.1 m), $\Phi_{0.1}$, and head level for a standing person (1.7 m), $\Phi_{1.7}$, as well as the average temperature in the occupied zone, Φ_{OZ} , are defined by Equations 2, 3 and 4. In this paper, we define the average temperature in the occupied zone, T_{OZ} , as the average of $T_{0.1}$ and $T_{1.7}$.

$$\Phi_{0.1} = \frac{T_{0.1} - T_s}{T_r - T_s} \quad (2)$$

$$\Phi_{1.7} = \frac{T_{1.7} - T_s}{T_r - T_s} \quad (3)$$

$$\Phi_{OZ} = \frac{T_{OZ} - T_s}{T_r - T_s} \quad (4)$$

For displacement ventilation systems according to Chen and Glicksman (Chen and Glicksman 2003) $\Phi_{0.1}$ varies between 0.2 and 0.7. According to Nielsen between 0.3 and 0.7 (Nielsen 1993). Mundt (Mundt 1996; Skistad 2002) developed a model for the prediction of $\Phi_{0.1}$ for displacement ventilation systems that is a function of the airflow rate and it is based on a heat transfer model between the ceiling and the floor. Mundt's equation is used in a cooling airflow design modelling tool developed by Chen and Glicksman [3]. We expect that most of the UFAD diffusers (e.g. swirl, linear bar grille, VAV directional, etc.) create less stratification than displacement ventilation due to increased mixing. $\Phi_{0.1}$ for UFAD system is likely to be higher than for DV systems. It is expected, but yet not proven, that underfloor displacement ventilation diffusers may generate similar $\Phi_{0.1}$ than typical wall displacement diffusers.

Lin and Linden (Lin and Linden 2005) and Liu and Linden (Liu and Linden 2008; Liu and Linden 2006) theoretically developed and experimentally tested (in a small-scale salt-tank model) a prediction of Φ for underfloor air distribution system as a function of the non-dimensional parameter, Γ (Gamma). Their model was used to develop stratification prediction based on full-scale experiments by Webster et al. (Webster 2007); The Γ - Φ_{OZ} equations obtained by Webster et al. have been implemented in the EnergyPlus UFAD module (Liu and Linden 2008; US Department of Energy ; Webster 2008b). The Γ - $\Phi_{0.1}$ and Γ - $\Phi_{1.7}$ equations have been implemented in the online CBE UFAD design tool (Bauman 2010; Schiavon 2010) and in previous versions of the tool (Bauman 2007b).

For perimeter zones, Γ was developed based on theory of line plumes generated by heat gain from exterior windows and walls. In this case a linearized formulation for Γ is used:

$$\Gamma = \frac{Q \cdot \cos \theta}{(n \cdot A_d) \cdot (0.0281 \cdot W_L)^{1/3}} \quad (5)$$

Where, Q is the total perimeter zone airflow [m^3/s]; θ is the discharge angle from vertical [$^\circ$]; n number of diffusers [-]; A_d is the effective diffuser area of single diffuser [m^2]; and W_L is the zone extraction rate per unit length of the perimeter zone [kW/m]. The effective diffuser area is always

smaller than the geometrical or free area of the diffuser and should be determined experimentally. Γ for interior zones is described in (Schiavon 2010).

The diffuser fluid-dynamic characteristics affect the temperature stratification in the room. Laboratory measured data are needed to obtain the Γ - Φ relationships required to predict stratification in the room.

The purpose of this study was to empirically characterize the influence of linear bar grilles and VAV directional diffusers on thermal stratification in perimeter zones for underfloor air distribution systems by developing Γ - Φ regression equations.

METHODS

Experimental facilities and room description

The experiments were carried out in a climatic chamber (4.88 m x 4.88 m x 4.5 m) equipped with a raised floor (height 0.48 m) and suspended ceiling (1.28 m) at 2.75 m from the top of the raised floor. The area of the climatic chamber is 23.8 m². The climatic chamber is adjacent to a solar simulator chamber (2.1 m x 4.9 m x 4.5 m). The two chambers are separated by a wall with a clear glass double pane window (width of 4 m and height of 2.26 m). The shading coefficient (SC) is 0.72, the solar heat gain coefficient (SHGC) is 0.62 and the overall U-value is 1.87 W/(m²·K). White venetian blinds are installed in the climatic chamber. The walls have similar construction and thermal properties. Starting from the exterior, the chamber wall is comprised of 12.7 mm of rigid board insulation consisting of a glass-fiber-reinforced polyisocyanurate foam core laminated between reflective aluminum foil facers on both sides (R-value=0.58 (m²·K)/W) and 0.15 m of icynene foam insulation (R-value=3.87 (m²·K)/W). The floor is composed of 0.15 m of concrete, 0.15 m of icynene foam insulation (R-value=3.87 (m²·K)/W) and 19 mm of plywood (R=0.165 (m²·K)/W). The top layer of the return plenum is comprised of 0.2 m of concrete, 0.19 m of icynene foam insulation (R-value=4.84 (m²·K)/W) and 12.7 mm of plywood (R=0.11 (m²·K)/W). The ceiling construction is thermally equivalent to a middle floor return plenum ceiling slab of a standard US commercial building. The thermal conditions in the climatic chamber and in the chamber with the solar simulator can be independently controlled. The chambers are located within a large conditioned test hall and can be considered almost adiabatic because the temperature difference between inside and outside is small and the thermal insulation high.

Air is supplied to the underfloor plenum from an air handling unit. Air is exhausted through ceiling-level return grilles. Office heat sources were modeled using a floor-mounted tower computer, flat screen and, overhead lighting. Occupants were simulated with thermal manikins that emit the same sensible load as a person doing office work (75 W). The manikins were wrapped with heat tape and dressed with light clothing similar to office attire. The heat output of the thermal manikins also matched the typical radiant/convective split of a person. More information about the manikins can be found in (Webster 2007). The internal heat gains are summarized in Table 1. In order to obtain a wide range of test conditions during the experiments, the number of occupied desks and overhead lights were changed.

Table 1. Internal heat source summary.

Heat source	Power [W]	Power [W/m ²]
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Workstation A	Personal computer	33	6.1
	Computer monitor	38	
	Thermal manikin	75	
Workstation B	Personal computer	32	6.0
	Computer monitor	35	
	Thermal manikin	75	
Workstation C	Personal computer	31	6.0
	Computer monitor	36	
	Thermal manikin	75	
Overhead lights		229	9.61
Measuring instruments and data acquisition		18	0.8
Total		677	28.4

Figure 1. Climatic chamber: a) Layout of test chamber b) photo of the thermal manikins, desks and solar simulator.

Measuring instruments and uncertainty

The air temperatures were monitored continuously with thermocouples. All the thermocouples were shielded against radiant heat transfer with an aluminized Mylar cylinder (see Figure 1). The sensors were calibrated prior to the measurements (Fluke 9102S dry-well calibrator). The obtained accuracy was $\pm 0.25^{\circ}\text{C}$ or better. The air temperature was measured at six heights (0.1, 0.6, 1.2, 1.7, 2.2, and 2.6 m) in five stratification trees shown in Figure 1. The supply and exhaust air was measured with multiple thermocouples spatially separated and series linked in order to obtain a spatial average of the air flow temperature. The accuracy was $\pm 0.25^{\circ}\text{C}$ or better. The propagated uncertainty on Φ has been calculated according to ISO guideline (ISO 1993) with a level of confidence of 95% (coverage factor of 2). The uncertainty depends on Φ and is, on average, less than ± 0.09 . The effective area, A_d , was measured with a duct blaster (The Energy Conservatory) and has an uncertainty of $\pm 3\%$ of the reading. The angle was visually assessed and the estimated uncertainty is $\pm 5^{\circ}$. The air flow rate was measured with differential pressure drop meter (Setra 264, accuracy $\pm 0.25\%$ of full scale) across a flow grid (Thermo-Scientific NZP series). The sensors were calibrated prior to the measurements. Six pressure meters were available and the one with a range most suited for the input airflow rate was used in each experiment to increase accuracy. The obtained accuracy was $\pm 1\%$ of air flow reading or better.

Solar simulator

The solar simulator was designed to simulate solar loads representative of those encountered in real buildings as accurately as possible. To replicate how solar gains create load in the space, it is important that the lamp array should: 1) match the solar spectrum distribution; 2) have a total output representative of actual conditions; and 3) be adjustable in order to achieve incident angles required, depending on the climate reference location selected.

High intensity discharge (HID) lamps using 1000 W metal halide bulbs were found to be a good candidate for the solar simulator. The spectral distribution of these lamps was measured using a special thermopile that allowed the measurement of the fraction of total radiation in each of the spectral bands, ultraviolet (UV), visible, and infrared (IR). These results were compared to those of the solar spectrum and shown to compare favorably as shown in Table 2 below.

Table 2. Comparison of spectral band energy fractions between high intensity discharge lamps and sun

Spectral band	Wavelength range [μm]	Solar bands fraction	HID lamp fraction
Ultraviolet	0.28-0.4	0.10	0.11
Visible	0.4-0.78	0.50	0.61
Infrared	0.78-2.8	0.40	0.29

During spectral testing the efficiency of the lamps was measured and found to be ~30%. The number of lamps required was determined from the calculated lamp output (based on the measured efficiency) and the requirements for the reference location, which in this case is Kansas City (USA) in July for a west facing window with a typical solar heat gain coefficient (SHGC) of 0.35 and incident insolation of 725.5 W/m^2 of glass area. Since the laboratory window is double clear glass with SHGC of 0.7 the actual output level represents a window with an SHGC of 0.40. Part load conditions are achieved using perforated metal screens since the lamps cannot be modulated and turning some off creates a non-uniform exposure. Two screen types were created with 67% and 33% open area, respectively. During the experiment the environmental chamber containing the solar simulator was air conditioned and kept at a specific temperature (depending on the experiment).

Diffusers characteristics

Two diffuser types were tested (two different manufacturer's products for each type): Variable air volume (VAV) directional and linear bar grille diffusers. A detailed description of the diffusers can be found in Webster et al. (Webster 2007). Hereafter only information related to the diffuser characteristics relevant for the Γ - Φ model will be reported. For the purpose of this study, each diffuser can be described by: the effective area (A_d) and the discharge angle specific to the diffuser type (θ). A_d and θ for the diffusers tested are reported in Table 3.

Table 3. Geometric diffuser characteristics needed for the Gamma-Phi calculations.

Diffuser	Effective area, A_d [m^2 (in^2)]	Angle, θ [$^\circ$]	$\cos \theta$
VAV directional A (AirFixture) - VAVDA	0.0353 (54.72)	45	0.707
VAV directional B (AirFixture) - VAVDB	0.0275 (42.65)	34.5	0.824
Linear bar grille A (AirFixture) - LBGA	0.0970 (150.28)	15	0.966
Linear bar grille B (Titus) - LBGB	0.1037 (160.7)	15	0.966

The VAV directional diffusers operate with constant underfloor plenum pressure (i.e., 12.5 Pa (0.05 iwc)) and constant outlet velocities leaving the diffusers. They have a square shape (0.29 x 0.29 m). In order to vary the amount of airflow entering the room, there are two options: 1) varying the effective area of the diffuser by moving a damper plate; 2) varying the time ratio between when the diffuser is fully open versus when it is fully closed. Linear bar grille diffusers are standard products that are routinely used in OH systems and are commonly employed in UFAD systems for heating and cooling in the perimeter zone. They come in various lengths and widths but usually have a discharge angle of 15° generated by a lip on the bars that directs the flow away from the window. We tested a linear bar grille of 0.15 by 1.83 m (6 in by 6 ft).

Experimental conditions and procedure

Forty seven experiments were conducted. The experiments are summarized in Table 4. The experiments are named according to the diffuser type and numbered in sequential order. The experiments were randomized within a block (diffuser type) (Montgomery 2008). The number of diffusers was varied in order to obtain a large variation in Γ . The heat gains were derived from the workstation (computer, manikin, desk lamp and measuring instrument), the overhead lighting systems and the solar gains. The combination and intensity of these gains were modified in order to obtain a large variation in Γ . The workstation load was varied by turning on one or two or three workstations. Overhead lighting levels were also varied. The solar load is provided by the HID lamps (direct radiation, infrared and convection from the window inside surface) and secondly from transmission gains from the solar chamber to the testing chamber. The solar load was regulated by adding screens to the lamps and changing the setpoint temperature in the chamber. For most of the experiments the solar chamber was controlled at 32°C.

The zone extraction rate was calculated based on airflow rate and the difference between return air temperature and diffuser discharge temperature. To calculate W_L the zone extraction rate was divided by the length of the perimeter zone, 4.88 m. The extraction rate is the rate at which sensible heat is removed from the conditioned space and it is equal to the cooling load only if the room air temperature is constant (RW.ERROR - Unable to find reference:249). The sum of the internal gains is not equal to the zone extraction rate because part of the heat is transferred to the supply plenum which creates temperature gain in the plenum. Plenum temperature rise (also known as thermal decay) is the difference between the air temperature at the diffuser, T_s , and supplied into the plenum, T_p (Lee 2012). The data were collected for 10 minutes after steady state conditions were reached. Steady state was determined when the air temperatures and surface temperatures changed less than 0.1°C during the last 30 minutes.

Table 4. Experimental input parameters.

Test	Number of diffusers	Window Blinds	Workstation [W]	Lighting [W]	Solar [W]	Q [m ³ /s]	W _L [kW/m]
VAVDA-1	2	Up	439	229	2169	0.189	0.422
VAVDA-2	1	Up	163	0	1978	0.142	0.319
VAVDA-3	3	Up	161	0	2219	0.141	0.353
VAVDA-4	1	Up	305	229	852	0.099	0.210
VAVDA-5	2	Up	439	229	1107	0.123	0.264
VAVDA-6	3	Up	303	0	808	0.071	0.150
VAVDA-7	2	Up	438	229	2369	0.259	0.462
VAVDA-8	3	Up	438	229	2435	0.212	0.496
VAVDA-9	2	Up	438	229	2333	0.189	0.464
VAVDA-10	3	Up	438	229	1965	0.208	0.392
VAVDA-11	2	Up	442	229	1869	0.186	0.369

VAVDA-12	1	Up	165	0	1742	0.140	0.267
VAVDA-13	2	Up	166	229	756	0.074	0.150
VAVDA-14	2	Down	442	229	1316	0.190	0.316
VAVDA-15	3	Down	438	229	1324	0.212	0.337
VAVDA-16	1	Down	165	0	1232	0.136	0.215
VAVDA-17	2	Down	444	229	1185	0.255	0.314
VAVDA-18	2	Up	447	229	1828	0.254	0.377
VAVDA-19	3	Up	300	0	711	0.072	0.139
VAVDA-20	3	Down	292	0	656	0.072	0.140
VAVDB-1	1	Up	165	0	1849	0.139	0.287
VAVDB-2	2	Up	441	229	1929	0.183	0.388
VAVDB-3	2	Up	167	229	733	0.074	0.151
VAVDB-4	2	Up	444	229	767	0.122	0.212
LBGA-1	1	Up	437	229	2148	0.260	0.410
LBGA-2	0.5	Up	435	229	2651	0.270	0.459
LBGA-3	1	Up	160	0	2237	0.165	0.348
LBGA-4	1	Up	304	229	895	0.106	0.209
LBGA-5	1	Up	160	0	750	0.066	0.114
LBGA-6	1.61	Up	162	0	805	0.066	0.121
LBGA-7	1	Up	444	229	2357	0.212	0.471
LBGA-8	0.5	Up	301	0	1993	0.179	0.295
LBGA-9	1	Up	443	229	2155	0.283	0.416
LBGA-10	1	Up	437	229	2444	0.236	0.483
LBGA-11	1	Up	440	229	2447	0.213	0.484
LBGB-1	1	Up	159	0	2091	0.166	0.338
LBGB-2	1	Up	437	229	1499	0.257	0.305
LBGB-3	0.5	Up	439	229	1733	0.266	0.356
LBGB-4	0.5	Up	305	0	1646	0.177	0.262
LBGB-5	1	Up	304	229	804	0.105	0.194
LBGB-6	1	Up	160	0	697	0.066	0.112
LBGB-7	1	Up	159	0	762	0.057	0.110
LBGB-8	1	Up	446	116	1808	0.211	0.358
LBGB-9	0.5	Up	300	0	1585	0.178	0.257
LBGB-10	1	Up	440	229	1561	0.286	0.315
LBGB-11	1	Up	437	229	1739	0.240	0.363
LBGB-12	1	Up	438	229	1709	0.227	0.349

Statistical analysis

The data distributions are described with median and first and third quartile in parenthesis. Regression models were compared with ANOVA. Regression models were selected based on R-squared adjusted values. R-squared, the coefficient of determination of the regression line, is defined as the proportion of the total sample variability explained by the regression model. The regression linear hypotheses have been visually evaluated for all the studied models (e.g. residuals vs. fitted values, normality, the square root of the standardized residuals versus the fitted values and Cook's distance). Segmented regression (Muggeo 2008) (aka piecewise regression) was applied but the benefits were limited and therefore excluded for the final models. For all tests the results were considered statistically significant when $p < 0.05$. The statistical analysis was performed with R version 2.13.1 [18]. Graphs were developed using GGplot2.

RESULTS AND DISCUSSION

The main performance parameters of the tested diffusers obtained in the experiments are summarized in Table 5. The results are described with median and first and third quartile in parenthesis. W_L is equal to 0.316 (0.110-0.382) kW/m. The air flow rate is equal to 0.0.179

(0.114-0.286) m³/s. The temperature in the occupied zone is equal to 24.8 (24.4-25.4) °C. These occupied zone temperatures are within the suggested comfort range for typical cooling conditions (ANSI/ASHRAE 2010). The objectives of the experiments were not to create comfort conditions but get enough variation on Γ in order to be able to develop Γ - Φ relationships.

The plenum temperature rise (thermal decay) is equal to 3.0 (2.45-3.45) K that is very close to the distribution obtained with energy simulation and equal to 3.7 (2.4-4.7) K (Lee 2012). Γ is equal to 9.1 (6.0-12.4), $\Phi_{0.1}$ is equal to 0.70 (0.60-0.85), Φ_{0Z} is equal to 0.80 (0.70-0.90), and, $\Phi_{1.7}$ is equal to 0.90 (0.80-1.00). The results shows that, for the diffuser testes, the stratification obtained with UFAD ($\Phi_{0.1}$ =0.70) is generally less than that obtained with displacement ventilation ($\Phi_{0.1}$ = 0.2-0.7 (Chen and Glicksman 2003)). Stratification is inversely related to Φ . At head height (1.7 m for a standing occupant) the temperature is almost equal to return temperature.

Table 5. Experimental results.

Test	T_s	$T_{0.1}$	T_{0Z}	$T_{1.7}$	T_r	T_s-T_p	Γ	$\Phi_{0.1}$	Φ_{0Z}	$\Phi_{1.7}$
VAVDA-1	17.8	24.2	24.8	25.4	26.6	3.3	8.3	0.7	0.8	0.9
VAVDA-2	17.8	25.2	26.0	26.7	26.7	3.3	13.7	0.8	0.9	1.0
VAVDA-3	18.2	24.8	25.3	25.9	28.2	3.8	4.4	0.7	0.7	0.8
VAVDA-4	18.8	24.8	25.3	25.8	27.2	3.0	10.9	0.7	0.8	0.8
VAVDA-5	18.8	23.9	24.5	25.1	27.3	3.2	6.3	0.6	0.7	0.7
VAVDA-6	19.9	24.7	26.0	27.4	28.3	4.4	2.9	0.6	0.7	0.9
VAVDA-7	18.0	24.4	24.7	24.9	25.1	2.5	11.1	0.9	0.9	1.0
VAVDA-8	18.2	23.9	24.5	25.0	27.5	2.6	5.9	0.6	0.7	0.7
VAVDA-9	17.6	24.3	24.9	25.6	27.4	3.2	8.0	0.7	0.8	0.8
VAVDA-10	18.4	23.9	24.5	25.1	25.9	2.8	6.2	0.7	0.8	0.9
VAVDA-11	17.7	23.9	24.7	25.4	25.6	3.2	8.5	0.8	0.9	1.0
VAVDA-12	18.0	25.2	25.5	25.8	25.6	3.5	14.3	0.9	1.0	1.0
VAVDA-13	19.1	24.1	25.0	26.0	27.1	4.6	4.6	0.6	0.7	0.9
VAVDA-14	16.3	21.0	21.4	21.9	22.9	1.9	9.2	0.7	0.8	0.8
VAVDA-15	16.9	20.8	21.5	22.1	23.2	1.3	6.7	0.6	0.7	0.8
VAVDA-16	16.5	21.7	22.3	22.9	22.8	2.1	15.0	0.8	0.9	1.0
VAVDA-17	16.6	20.7	21.1	21.4	21.5	1.1	12.4	0.8	0.9	1.0
VAVDA-18	17.7	23.3	23.6	24.0	23.6	2.1	11.6	1.0	1.0	1.1
VAVDA-19	19.4	23.3	24.5	25.7	27.0	3.8	3.1	0.5	0.7	0.8
VAVDA-20	18.7	22.0	23.2	24.4	26.4	3.0	3.0	0.4	0.6	0.7
VAVDB-1	18.1	24.6	25.3	26.0	26.3	3.6	20.7	0.8	0.9	1.0
VAVDB-2	17.6	23.9	24.6	25.2	26.0	3.1	12.4	0.8	0.8	0.9
VAVDB-3	18.9	24.2	25.1	25.9	27.0	4.3	6.8	0.7	0.8	0.9
VAVDB-4	18.2	22.8	23.4	24.0	25.1	2.7	10.1	0.7	0.7	0.8
LBGA-1	19.2	24.9	25.1	25.3	25.5	2.5	11.5	0.9	0.9	1.0
LBGA-2	19.9	26.7	26.7	26.8	26.7	3.2	22.9	1.0	1.0	1.0
LBGA-3	19.0	24.7	25.4	26.0	27.3	3.4	7.7	0.7	0.8	0.8
LBGA-4	19.8	23.9	24.9	25.8	27.7	3.1	5.9	0.5	0.6	0.8
LBGA-5	20.8	24.4	25.8	27.2	27.6	4.4	4.5	0.5	0.7	0.9
LBGA-6	20.5	24.1	25.7	27.4	27.8	4.6	2.7	0.5	0.7	0.9
LBGA-7	18.9	24.8	25.4	26.0	27.7	2.8	8.9	0.7	0.7	0.8
LBGA-8	19.4	26.7	26.6	26.5	26.0	3.9	17.7	1.1	1.1	1.1
LBGA-9	19.0	24.5	24.8	25.2	24.8	2.3	12.4	0.9	1.0	1.1
LBGA-10	19.3	24.7	25.2	25.7	27.4	2.6	9.8	0.7	0.7	0.8
LBGA-11	18.4	24.3	25.0	25.6	27.5	2.9	8.9	0.7	0.7	0.8
LBGB-1	18.5	23.2	24.0	24.9	26.6	2.9	7.3	0.6	0.7	0.8
LBGB-2	18.8	23.9	24.4	24.8	23.5	2.1	11.7	1.1	1.2	1.3
LBGB-3	18.7	24.5	24.8	25.2	24.0	2.0	23.0	1.1	1.2	1.2

LBGB-4	18.6	25.4	25.7	26.1	24.5	3.1	16.9	1.1	1.2	1.3
LBGB-5	19.7	23.3	24.7	26.0	27.1	3.0	5.5	0.5	0.7	0.9
LBGB-6	20.6	23.9	25.4	26.9	27.3	3.8	4.2	0.5	0.7	0.9
LBGB-7	20.0	23.8	25.6	27.3	27.8	5.5	3.6	0.5	0.7	0.9
LBGB-8	18.5	23.4	24.0	24.6	25.2	2.4	9.1	0.7	0.8	0.9
LBGB-9	18.5	25.1	25.5	25.8	24.2	2.9	17.1	1.2	1.2	1.3
LBGB-10	18.7	23.7	24.2	24.8	23.0	2.0	12.9	1.1	1.3	1.4
LBGB-11	18.8	23.9	24.4	24.9	24.8	2.2	10.3	0.8	0.9	1.0
LBGB-12	18.5	23.5	24.0	24.6	24.6	2.4	9.9	0.8	0.9	1.0

Figure 2 Γ - Φ plots for the four diffusers tested (Linear bar grille A and B and VAV directional A and B) and for the three Φ ($\Phi_{0.1}$, Φ_{0z} and $\Phi_{1.7}$).

Figure 2 shows the Γ - Φ plots for the four diffusers (linear bar grille A and B and VAV directional A and B) and for the three Φ ($\Phi_{0.1}$, Φ_{0Z} and $\Phi_{1.7}$). The plots have been grouped according to the main diffuser typology to visually check if it would be reasonable to develop Γ - Φ equations for the main diffuser typology and not for each specific one. From Figure 2 it can be noticed that there are no substantial differences between LBGA and LBGB for $\Gamma < 11$, for higher Γ , LBGB tend to cause higher Φ than LBGA. For $\Gamma > 11$, Φ tends to be higher than 1, meaning that the system is overshooting and a reverse stratification is generated. For the linear diffuser the conditioned air can strike the ceiling generating a high risk of air short circuiting (thus, a waste of energy and clean air), and increased mixing which eliminates stratification. Linear diffusers should be operated at $\Gamma < 11$. For this reason, a unique Γ - Φ relationship was created because the LBG is expected to operate at low Γ and, if Γ is high, all the benefits related to stratification are lost.

From Figure 2 it is clear that there are no substantial differences between VAV directional A and B and these two could be described by the same model. This does not mean that their performance is the same because the effective area and angle are different. For the same airflow rate, number of diffuser and cooling extraction rate VAVDA generates a lower Γ than VAVDB due to the smaller area and higher angle. Therefore, VAVDA generates a higher stratification than VAVDB. By comparing the linear bar grille diffusers with the VAV directional diffuser it can be concluded that VAV directional diffusers tend to create a stronger stratification and therefore better utilize the energy and air quality advantages related to stratified systems.

Effect of blinds

Figure 3 shows the effect of lowered blinds on the stratification (Γ - $\Phi_{0.1}$ relationship). Ten experiments are plotted, five with the blinds and five without the blinds. All the experiments were performed with the VAV directional diffusers. White venetian blinds were used to fully cover the area of the window. The blinds were located inside the room. During the experiments with the blinds, the short wave radiation from the lamps was fully blocked by the blind slots. For similar Γ values, the only difference between one experiment and the other was the presence of the blinds. From the figure can be deduced that the presence of blinds causes an increase on thermal stratification (reduction of $\Phi_{0.1}$). The regression line for the experiments with the blinds was forced to have the same slope than the case without blinds in order to obtain a constant offset caused by the presence of the blinds. The total explained variance was reduced of only 2% (from R^2 of 0.92 to 0.90). From the difference in the intercepts of the single variable linear regression can be calculated that, on average, the presence of the blinds reduce $\Phi_{0.1}$ of 0.13 (e.g. from 0.80 to 0.67). This time, we did not collect data about the effect of lowering the blinds on stratification when linear bar grilles are used. We previously showed with laboratory measurements that stratification increases when linear bar grilles are used (Bauman 2007b). Therefore, for the online CBE UFAD design tool (Bauman 2010; Schiavon 2010) we will apply the same $\Phi_{0.1}$ reduction that was obtained for VAVD.

Figure 3. Effect of the blinds on thermal stratification (Γ - $\Phi_{0.1}$ relationship).

Γ - Φ relationships

Figure 4 shows the developed Γ - Φ relationships for two tested diffuser types: linear bar grilles and VAV directional. Figure 4 reports also the 95% confidence intervals. The models are mathematically described in Table 6. For developing the VAVD models the experiment VAVDB-1 has been removed because it creates a leveraging effect. Blinds had a significant effect only for $\Phi_{0.1}$. The ANOVA analysis of the regression models indicated that all the models are significant ($p < 0.001$) and the Adjusted R-squared is in the figure and in the table. The hypotheses of the linear regression models were verified, and thus, the models are valid. The online publicly available UFAD cooling load design tool, developed by the Center for the Built Environment at UC Berkeley (<http://www.cbe.berkeley.edu/ufad-designtool/online.htm>), has been updated with the new Γ - Φ relationships.

Table 6. Γ - Φ relationships at 0.1m, occupied zone and 1.7m.

Diffuser Type	Γ - $\Phi_{0.1}$	Γ - Φ_{0z}	Γ - $\Phi_{1.7}$
Linear bar grille - perimeter	$\Gamma \leq 2.7$; $\Phi_{0.1} = 0.3582$ $2.7 < \Gamma \leq 23$; $\Phi_{0.1} = 0.1282 + 0.0908\Gamma - 0.0021\Gamma^2$ $\Gamma > 23$; $\Phi_{0.1} = 1.1074$ Remove 0.13 if blinds are down $R^2_{adj} = 0.86$	$\Gamma \leq 2.7$; $\Phi_{0z} = 0.5671$ $2.7 < \Gamma \leq 23$; $\Phi_{0z} = 0.5671 + 0.0301\Gamma$ $\Gamma > 23$; $\Phi_{0z} = 1.2594$ $R^2_{adj} = 0.60$	$\Gamma \leq 2.7$; $\Phi_{1.7} = 0.8305$ $2.7 < \Gamma \leq 23$; $\Phi_{1.7} = 0.7742 + 0.0208\Gamma$ $\Gamma > 23$; $\Phi_{1.7} = 1.2535$ $R^2_{adj} = 0.36$
VAV Diffuser - perimeter	$\Gamma \leq 2.9$; $\Phi_{0.1} = 0.5452$ $2.9 < \Gamma \leq 15$; $\Phi_{0.1} = 0.4605 + 0.0292\Gamma$ $\Gamma > 15$; $\Phi_{0.1} = 0.8987$ Remove 0.13 if blinds are down $R^2_{adj} = 0.64$	$\Gamma \leq 2.9$; $\Phi_{0z} = 0.6652$ $2.9 < \Gamma \leq 15$; $\Phi_{0z} = 0.5977 + 0.0233\Gamma$ $\Gamma > 15$; $\Phi_{0z} = 0.9472$ $R^2_{adj} = 0.65$	$\Gamma \leq 2.9$; $\Phi_{1.7} = 0.7719$ $2.9 < \Gamma \leq 15$; $\Phi_{1.7} = 0.7168 + 0.0190\Gamma$ $\Gamma > 15$; $\Phi_{1.7} = 1.0018$ $R^2_{adj} = 0.36$

Figure 4. Γ - Φ relationships, adjusted coefficient of determination, 95% confident intervals for the two diffusers type tested.

CONCLUSIONS

The main conclusions of this study are:

- The stratification obtained with the tested UFAD diffuser is generally lower than the one obtained with displacement ventilation. This is reflected by having $\Phi_{0.1}$ for UFAD in the range of 0.60-0.85 (warmer temperature) and for displacement ventilation in the range of 0.2-0.7 (cooler temperature). At head height, 1.7 m for a standing occupant, the temperature is almost equal to the return temperature.
- The plenum temperature rise (thermal decay) is equal to 3.0 (2.45-3.45) K.
- Linear bar grille diffusers may create a reverse stratification and thus waste energy and clean air, and increase mixing thus eliminating stratification. The developed Γ - Φ relationships may help the designer and operator to avoid this condition.
- VAV directional diffusers tend to create more stratification than linear bar grille diffusers and therefore better utilize the energy and air quality advantages related to stratified systems.
- Γ - Φ relationships for the two diffuser types and three heights have been developed.
- Lowering internal blinds causes an increase in thermal stratification (0.13 reduction of $\Phi_{0.1}$) for VAV directional diffusers.

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