Title

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A COMPARISON BETWEEN TWO UNDERFLOOR AIR DISTRIBUTION (UFAD) DESIGN TOOLS

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SUMMARY

The purpose of this study is to compare the capabilities and accuracy of two publicly available underfloor air distribution (UFAD) design tools (ASHRAE RP-1522 and CBE). The comparison is based on the air distribution models, diffuser types, ability to predict the design cooling load, supply plenum heat balance, temperature profile and setpoint, plenum configuration, and air distribution effectiveness. A combined database is fed into each tool's air distribution model to assess their accuracy. The results show the RP-1522 model predicts thermal stratification slightly more accurately than the CBE model in cases using swirl and square diffusers, but both results are comparably accurate for design purposes. The CBE UFAD tool has the key advantage of being able to predict the UFAD cooling load and model four different plenum configurations and both interior and perimeter zones. The RP-1522 tool is able to calculate the air distribution effectiveness.

INTRODUCTION

Underfloor air distribution (UFAD) is an 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. 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, 2013a).

As UFAD has attracted growing interest and achieved market penetration (Bauman et al., 2010), it is very important and convenient to have a simplified and accurate tool for engineers to develop their design. Currently there are two available design tools for determining zone airflow requirements for UFAD systems (ASHRAE, 2013a), one, named here the RP-1522 tool, was developed as result of the ASHRAE Research Project (RP-1522) (Jiang et al., 2012). It is an airflow design tool able to predict the vertical temperature difference between the head and ankle of occupants and the supply airflow rate for one zone under cooling conditions. The other one, named here the CBE UFAD tool, was developed at Center for the Built Environment (CBE) at University of California Berkeley (Schiavon et al., 2010a). It is capable of predicting the design cooling load, airflow rate, room air stratification and plenum air temperature gain for both interior and perimeter zones (ASHRAE, 2013a).

The objectives of this study were to compare: (1) the features of the RP-1522 and the CBE UFAD tools based on the design cooling load, air distribution models, thermal stratification profile, supply plenum cooling load, plenum configurations and diffuser types; and (2) the accuracy of thermal stratification predictions of the two tools versus a database composed of CFD simulations (RP-1522) and full-scale experiments (CBE).

COMPARISON OF FEATURES

Design cooling load

Cooling load profiles for UFAD and overhead (OH) systems are different (Schiavon et al., 2011). The difference is primarily due to the thermal storage effect of the lighter-weight raised floor panels compared to the heavier mass of a structural floor slab, as well as the enhanced rate of zone heat removal due to radiant heat transfer (Schiavon et al., 2010b). A new index, named UFAD cooling load ratio (UCLR), which is defined by the ratio of the peak cooling load calculated for UFAD to the peak cooling load calculated for a well-mixed system, was developed to calculate the cooling load for UFAD system. The CBE UFAD tool is able to calculate the UFAD cooling load for each zone with the UCLR when the traditional peak cooling load has been calculated for an overhead (well-mixed) system.

The ASHRAE RP-1522 tool does not calculate the cooling load as it was not the objective of the project, but accepts two cooling loads as an input ("equipment, occupants and lighting" and "solar heat flux"). It requires users to obtain the UFAD design cooling load from energy simulation programs (like EnergyPlus) or those methods described in ASHRAE Fundamentals Handbook (Zheng et al., 2012). There is one main limitation with this approach: if the designers employ EnergyPlus, then the use of a simplified tool to predict cooling airflow rate is not needed. The simplified tool, however, can still be used to obtain a more precise temperature profile.

Air distribution models for predicting thermal stratification

The CBE UFAD tool uses the Gamma (Γ)-Phi (Φ) model to predict thermal stratification, which was developed from the study of Lin and Linden (2005) and Liu and Linden (2006). Γ is a non-dimensional parameter representing the relative strengths between buoyancy and momentum forces; Φ is the local non-dimensional temperature of the space. Lin and Linden (2005) showed that the buoyancy flux generated by the heat source and the momentum flux from the diffuser discharge are the two governing parameters for the thermal stratification. The empirical equations correlating Γ and Φ were developed from laboratory experiments (Schiavon et al., 2010a; Webster et al., 2007). Because the experimental data for the Γ-Φ model was primarily focusing on office layouts, the CBE UFAD tool has the limitation that it is mainly applicable to office buildings. Γ- Φ model requires the users to specify the number of thermal plumes for the design calculation, which is referred as the number of occupants in CBE UFAD tool. The formulation of Γ is different for the interior and perimeter zones, and more information can be found in Schiavon et al. (2010a).

The RP-1522 tool uses the Archimedes number, which is the ratio between the buoyancy and inertial forces. Xue et al. (2012) showed that the convective heat gain in the occupied zone contributes to room air thermal stratification due to buoyancy while the inertial force from the diffuser discharge provides mixing. An empirical quadratic regression model was developed from the CFD simulation database. The model correlates the Archimedes number with the temperature difference in the occupied zone $\Delta T_{oc} = T_{head} - T_{ankle}$, and is implemented in RP-1522 tool. For the detailed equations, please refer to Jiang et al. (2012). The main advantage of RP-1522 tool is that it can be applied to various types of building layouts, such as classrooms, workshops, restaurants, retail shops, conference rooms and auditoriums, as well as offices. However, there's no input in the tool's interface to allow the users to specify the height of the zone and it has the default built-in value of 2.43 m. This limits the RP-1522 tool's application to spaces with high ceilings, like auditoriums.

Thermal stratification profile

In a well-mixed system the air temperature measured at 1.2 m is considered representative of the thermal environment. This assumption is no longer valid when UFAD is used, which produces temperature stratification in the conditioned space as shown in Figure 1. Wyon and Sandberg (1996) showed that local and whole-body discomfort sensations is slightly affected by thermal gradient, but is strongly affected by average operative temperature. As equation 1 shows, the CBE UFAD tool uses the average occupied zone temperature ($T_{oz,avg}$) to better represent the acceptable comfort condition for standing occupants in a stratified room, on the assumption that the thermal sensation perceived by an occupant exposed to a stratified environment is close to that of an occupant exposed to a uniform air temperature equal to the average occupied zone temperature (Schiavon et al. ,2010a).

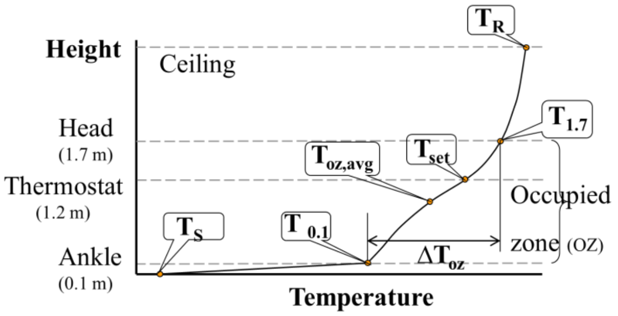

Figure 1 Example room air temperature profile in stratified UFAD room. (Schiavon et al., 2010a)

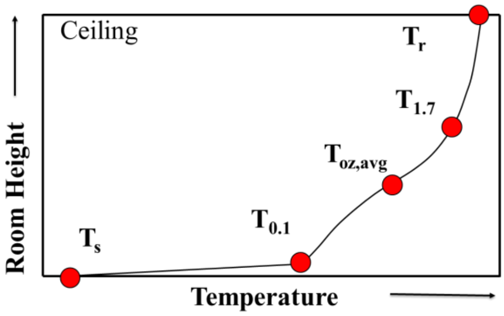

Figure 2 Computed temperature points in the thermal stratification model. (Jiang et al., 2012)

$$T_{oz,avg} = \left(\frac{1}{1.7-0.1}\right)\left[\left(\frac{1.7-0.1}{2}\right)(T_{1.7}+T_{set}) + \left(\frac{1.2-0.1}{2}\right)(T_{0.1}+T_{set})\right] \quad (1)$$

Where, $T_{1.7}$ = Air temperature at standing head level (1.7 m); T_{set} = Setpoint temperature at the thermostat level (1.2 m); $T_{0.1}$ = Air temperature at ankle level (0.1 m).

In ASHRAE RP-1522 tool, a different way of characterizing the temperature gradient is used to predict the thermal stratification of UFAD system as Figure 2 shows. The average temperature of occupied zone, $T_{oz,avg}$, is used to represent the comfort condition of the occupants in stratified thermal environment. $T_{oz,avg}$, equals the average temperature between T_{head} and T_{ankle}. It also assumes that the room design temperature T_x, which is the same as T_{set} in CBE UFAD tool equals the $T_{oz,avg}$ without considering the difference of occupants' thermal sensation between the stratified thermal environment and well-mixed condition. This might cause the calculation of supply airflow rate to be slightly larger than required.

Supply plenum cooling load

For UFAD systems, the cool supply air warms up significantly in the supply plenum, as described by Lee et al. (2012). The amount of heat entering the underfloor plenum directly influences the design cooling airflow rate. Hence, the UFAD cooling load is split into supply plenum, zone and return plenum cooling loads. Based on the research results from Schiavon et al. (2010a), three new indexes, which are supply plenum fraction (SPF), zone fraction (ZF) and return plenum fraction (RPF) were developed to split the total UFAD cooling load into three fractions in order to calculate the cooling airflow rate more accurately. Similar to UCLR, a regression equation for each of those indexes was developed based on EnergyPlus simulation results (Schiavon et al., 2011). Detailed information about the equations are reported in Schiavon et al. (2010a). The CBE UFAD tool is able to predict SPF with the user input of floor level, zone type and orientation.

ASHRAE RP-1522 tool requires the user to specify the fraction of the cooling load assigned to the supply plenum. This is a limitation because only with an advanced energy simulation (like EnergyPlus) can this be determined. Design load tools are not able to predict it. Jiang et al. (2012) developed an analytical heat transfer model for predicting heat loss to the supply plenum of the UFAD system, however it is not directly implemented into the design tool. Instead Jiang et al. suggested to use 30% to 40% according to the results of Bauman et al. (2006) which is less accurate than the method used in the CBE UFAD tool.

Comparison of plenum configurations

The CBE UFAD tool is able to model four plenum configurations (series, reverse series, independent and common). The supply plenum is a key component of a UFAD system, and can have an important impact on peak cooling loads for UFAD compared to an OH system. Due to the plenum temperature rise effect, the air temperature at the diffusers is warmer than the one supplied to the plenum. The supply air may take many different paths in the supply plenum, which will impact the temperature of the air leaving the diffusers. Therefore, providing different options for plenum configurations is essential to accurately predict the thermal stratification and comfort. The CBE UFAD tool allows the user to specify the temperature at the inlet of the plenum, representing the supply air temperature from the central air handler. The ASHRAE RP-1522 tool does not consider different plenum configurations and it is only able to calculate one zone at a time. It requires users to specify the supply air temperature at the diffuser or the ratio of plenum flow rate to zonal supply flow rate, which is difficult to get at the design stage.

Comparison of diffuser types

Both tools cover three diffuser types: swirl, square and linear bar grill diffusers. However there are slight differences in the specific diffusers that each tool used to build their models. As *Table 1 Comparisons of diffuser types in two UFAD design tools*shows, there are differences in the effective outlet area (A_d) of linear bar grille diffusers of the two tools, and the nominal air flow rate (V_d) for diffusers in the RP-1522 tool varies case by case.

Table 1 Comparisons of diffuser types in two UFAD design tools

Type		Diffuser Effective Area	Nominal Airflow Rate	Angle Specific to Diffuser Type	Angle Factor Specific to Diffuser Type
		A_d (m^2)	V_d (m^3/h)	θ (°)	Cos θ
Swirl	CBE	0.0075	122	28	0.883
	RP-1522	0.0075	variable	28	0.883
Square	CBE	0.0350	250	45	0.707
	RP-1522	0.0350	variable	45	0.707
Linear	CBE	0.0152	247	15	0.966
	RP-1522	0.0276	variable	15	0.966

For CBE UFAD tool, users can select from swirl and square diffuser for interior zones, square and linear bar grille diffusers for perimeter zones. The value of A_d and θ have the default settings built in CBE UFAD tool. In the current version of the tool, the user cannot change those values to match different diffuser designs For RP-1522 tool, users are required to input the operating airflow rate (V_d), and the effective outlet area (A_d) for each diffuser. This gives users more power to edit the characteristics of the diffusers. However, users have to check the diffuser catalogues or contact the manufacturers to get the precise information to use the tool.

Air distribution effectiveness

One of the advantages of RP-1522 tool is that it is able to calculate the air distribution effectiveness E_z to ensure that the predicted supply airflow rate meets ASHRAE requirements for acceptable indoor air quality. ASHRAE (ANSI/ASHRAE, 2010) defines the required minimum airflow rate of the zone, V_r, which is based on mixing ventilation where the ventilation effectiveness is 1.0. Lee et al. (2009) shows that UFAD has higher ventilation effectiveness. The required supply airflow rate (V_f) of fresh air in UFAD can be calculated by $V_f = V_r / E_z$. The empirical equations used to predict E_z in the stratified air distribution systems were developed in Lee et al. (2009). For the detailed equation, please refer to Lee et al. (2009). The CBE UFAD tool currently does not have the capability to calculate E_z.

NUMERICAL COMPARISON

A numerical comparison was performed to provide a quantitative assessment of the accuracy of the two tools. Given that the users could only specify the supply air temperature entering the plenum in CBE UFAD tool, it is not feasible to feed exactly the same inputs to both tools in order to keep the supply air temperature at the diffuser level (T_s) and return air temperature (T_R) the same. Therefore, only the air distribution models used to predict the thermal stratification is compared using a new UFAD database. In this case, the supply air temperature at the diffuser (T_s) and return air temperature (T_R) are kept the same for both models and the predicted temperature at the ankle level ($T_{0.1}$) will be compared.

The new UFAD database is a combination of 73 cases from the CBE full-scale experiments and 31 cases from the RP-1522 CFD simulations. All the cases are office building layout and the diffuser configurations are shown in

Table 2 Case configuration of combined database

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	Swirl	Square		Linear	Total
Zone type	Interior	Interior	Exterior	Exterior	
RP-1522	13	6	6	6	31
CBE	18	8	30	23	79

For CBE UFAD tool, Γ is calculated with the inputs of room airflow, diffuser effective area (A_d), discharge angle for diffuser flow (θ), number of diffusers, number of plumes and zone cooling load. Based on the Γ-Φ equations developed in Schiavon et al. (2011), $T_{0.1}$ could be obtained. For RP-1522 tool, zone area, room temperature, supply air temperature at diffuser (T_s), zone cooling load, flow rate (V_d) and effective area (A_d) of the diffuser were fed into the tool to calculate the temperature difference between head and ankle of a standing person. Then the ankle temperature could be calculated with Equation 2.

$$T_{0.1} = T_{set} - \frac{1}{2}\Delta T_{oc} \tag{2}$$

$T_{0.1}$ is used to compare the accuracy of each air distribution models predicting the thermal stratification profile. The comparison is done by calculating the coefficient of variation of the root mean square deviation, CV(RMSD), of $T_{0.1}$ determined by results from two tools versus those from the database. Root mean square deviation, RMSD, is commonly used as a measure of differences between simulated values and actual observed values. CV(RMSD) is the normalized RMSD by the average observed values and can be used to compare the accuracy of simulation methods.

$$CV(RMSD) = \frac{RMSD}{\bar{T}_i} = \frac{\sqrt{\left(\sum_{i=1}^{n}\left(T_i - \hat{T}_i\right)^2 / n\right)}}{\bar{T}_i} \tag{3}$$

where T_i is the measured temperature of the experiment, $\hat{T}_i$ is the predicted temperature, $\bar{T}_i$ is the averaged measured temperature of the experiment and n is the number of cases. In order to access whether each model is a good prediction model for UFAD system, a model prediction test as in the Mean Magnitude of Relative Error (MMRE) is performed. The MMRE in our case is defined as:

$$MMRE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{T_i - \hat{T}_i}{T_i}\right| \tag{4}$$

where T_i are temperatures from the database, $\hat{T}_i$are predicted temperature from each model and n is the number of cases. Evidently, $\varepsilon_i = (T_i - \hat{T}_i)/T_i$ is the relative error. A model with a value MMRE < 25% could be considered to be a reasonably good prediction model.

RESULTS AND DISCUSSION

The results of the numerical comparison for all three diffusers are shown in Figure 4.

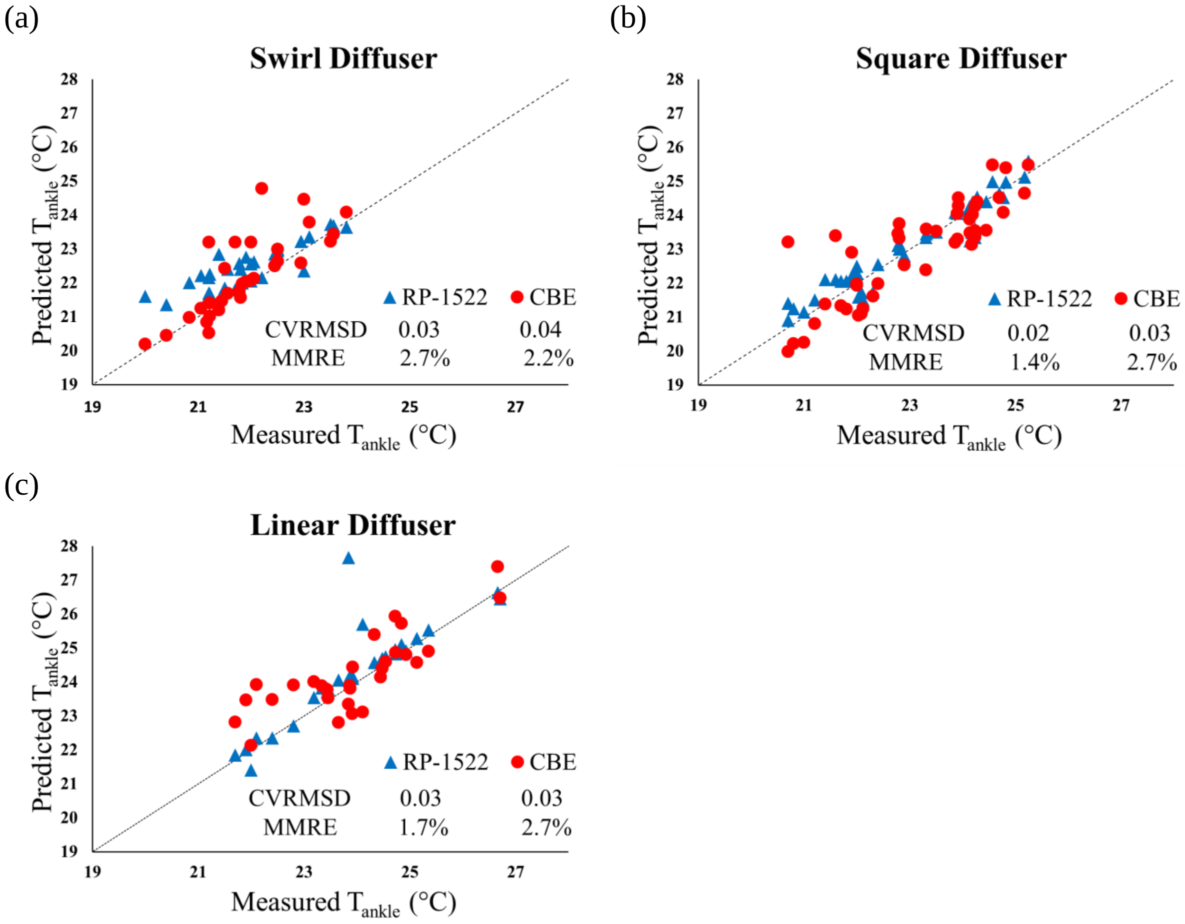

Figure 3 The comparison of $T_{0.1}$ with cases using swirl, square and linear bar grill diffusers

From the comparison of CVRMSD, the RP-1522 tool predicts slightly more accurately than the CBE UFAD tool for swirl (0.03 vs. 0.04) and square diffusers (0.02 vs. 0.03). For linear bar grille diffusers, the accuracy of both tools are about the same. The MMRE of both models in three cases are significantly less than 25%. For swirl diffusers, the MMRE of CBE UFAD tool is less than RP-1522 tool by 0.5%. For square and linear bar grill diffusers, the RP-1522 tool is less than CBE tool by around 1%. Due to the low values of MMRE, both models are comparably accurate prediction models for design purposes.

CONCLUSIONS

Both tools have practical advantages and limitations. CBE UFAD tool has the key advantage of being able to predict the UFAD cooling load. Besides that, the CBE UFAD tool is also able to calculate heat gain in the supply plenum, model different plenum configurations and zone types, but has the limitation of primarily being used in office buildings and not able to calculate air distribution effectiveness. RP-1522 tool covers more buildings types and is able to calculate the air distribution effectiveness, however requiring users to input the zone cooling load, supply plenum factor and the operating supply airflow rate of each diffuser, which is difficult to get during the design stage for UFAD system.

There are slight differences in terms of the accuracy to predict the thermal stratification of two tools. The RP-1522 tool predicts thermal stratification slightly more accurately than the CBE model in cases using swirl and square diffusers and they have the same accuracy in cases using linear diffusers. However, both models are acceptably accurate prediction models for design purposes.

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