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Analysis of cooling load calculations for underfloor air distribution systems

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Abstract

Underfloor air distribution (UFAD) systems use an underfloor supply plenum located between the structural floor slab and a raised floor system to supply conditioned air through floor diffusers or terminal units directly into the building's occupied zone. If designed properly, they have the potential to enhance energy efficiency, indoor air quality and building life cycle performance. However, the application of UFAD system is still obstructed by the information gap in some fundamental issues, such as cooling load calculation. All the cooling load calculation methods for UFAD systems nowadays have limitations and drawbacks and most building designers are not familiar with them. This research aims to investigate the cooling loads calculation methods for UFAD systems. Fundamental principles of UFAD with different configurations are studied to analyse the effects on cooling load components. Critical evaluation is made on the key factors and issues affecting the cooling load and how they differ from the overhead air distribution systems. It is found that thermal stratification, management of solar and lighting loads, architectural design and thermal properties of structural floor slab will influence the cooling load and must be evaluated carefully. It is hoped that the findings could improve the understanding of UFAD systems and provide practical information for performing the cooling load calculations and optimising the system performance.

Keywords

Underfloor air distribution systems; cooling load calculations.

1. Introduction

Underfloor air distribution (UFAD) systems use an underfloor supply plenum located between the structural floor slab and a raised floor system to supply conditioned air through floor diffusers or terminal units directly into the occupied zone (OZ) of the building (ASHRAE, 2013b; Lian and Ma, 2006; Zhang, *et al.*, 2014). They were firstly applied to the heating, ventilating and air-conditioning (HVAC) systems of computer rooms by integrating with the access floor systems and now they have also been used in offices and other commercial buildings (Bauman and Webster, 2001; Carrier Corporation, 2003; EDR, 2003). If designed properly, they have the potential to enhance energy efficiency, indoor air quality and life cycle performance of the building (Alajmi, and El-Amer, 2010; Daly, 2002; Filter, 2004). It is believed that UFAD systems and modular raised access floors can provide the best overall flexibility and long-term functionality in both construction and operation cost management to enhance the sustainability of buildings and HVAC systems (Hui and Li, 2002).

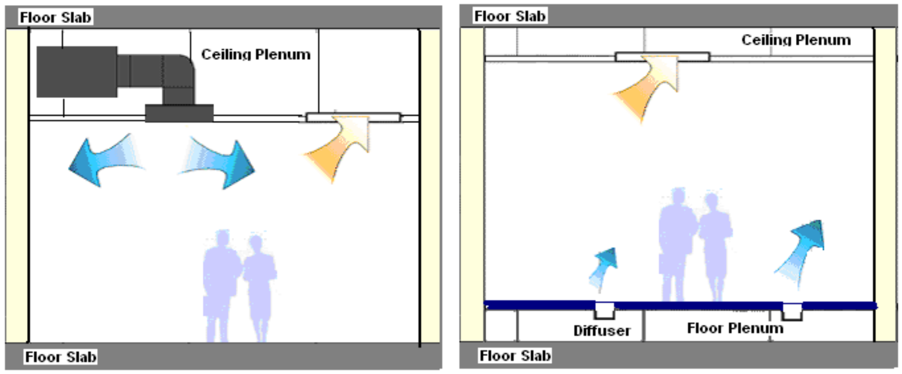
However, Zhang, *et al.* (2014) pointed out that the application of UFAD system is still obstructed by the information gap in some fundamental issues, such as cooling load calculation, control of the thermal stratification, and evaluation of energy consumption. In fact, the application of an UFAD system requires the building designer to view the design very differently because its air flow and thermal characteristics are different from the conventional overhead (OH) well-mixed systems (ASHRAE, 2013b; Carrier Corporation, 2003). UFAD system requires an integrated approach throughout the building design process from system design schematic stage, to load estimate, to commissioning (Filter, 2004); it also demands supplemental design and construction coordination regarding structural, air leakage, fire and smoke management, safety, and security issues (NIBS, 2005).

Design engineers often commented that the most important uncertain issue of UFAD system design is the design cooling load calculation (Bauman, Webster and Benedek, 2007). In fact, all the cooling load calculation methods proposed for UFAD systems nowadays have limitations and drawbacks (Yong and Ye, 2008) and most building designers are not familiar with them too (Zhang, *et al.*, 2014). Thus, there is a need to analyse the cooling loads calculations for different types and configurations of UFAD systems so as to develop practical and effective information for building designers and researchers to properly integrate, implement and evaluate the systems (Montanya, Keith and Love, 2009).

This research aims to investigate the cooling loads calculation methods for UFAD systems to enhance understanding of their characteristics and applications. Fundamental principles of UFAD systems with different configurations (such as supply plenum, air handling unit, fresh air system, diffusers, etc.) are studied in order to analyse their effects on cooling load components. Several methods and design tools currently used for the cooling loads calculation of UFAD systems are examined. Also, critical evaluation is made on the key factors and issues affecting the cooling load requirements and how they differ from the OH air distribution systems. It is hoped that the findings could improve the understanding of UFAD systems and provide practical information for performing the cooling load calculations and optimising the system performance.

2. Basic Principles of UFAD Systems

Modern UFAD systems were introduced in 1950s in Europe (Sodec and Craig, 1990) for rooms with high heat loads (typically 200 to 1000 W/m^2) such as computer rooms, control centres and laboratories; then later in 1970s, offices in South Africa, Germany, Japan and USA adopted these systems to cope with modernisation and increasing use of electronic equipment (Bauman and Webster, 2001; Loudermilk, 1999; Matsunawa, Iizuka and Tanabe, 1995). In the past decades, they have also been applied to other types of commercial and institutional buildings with an increasing penetration rate (ASHRAE, 2013b; Bauman and Webster, 2001; Bauman, *et al.*, 2007). Figure 1 shows the simplified diagrams to explain the concepts of OH and UFAD systems.



(a) Overhead distribution system (b) Underfloor air distribution system

Figure 1. Overhead and underfloor air distribution systems (Bauman, 2003)

2.1 Vertical Temperature Profile

UFAD systems are usually designed to provide partially mixed room conditions that vary between two extremes, fully mixed and thermal displacement (no mixing) (ASHRAE, 2013a, Chapter 20). Different from displacement ventilation (DV) systems, UFAD systems usually supply air to the space with higher velocity through smaller-sized outlets and can be controlled by individual occupants. Similar to DV systems, thermal stratification in the air with vertical temperature gradient often occurs in UFAD systems. Figure 2 shows a comparison of typical vertical temperature profiles for DV, UFAD, and conventional OH mixing systems.

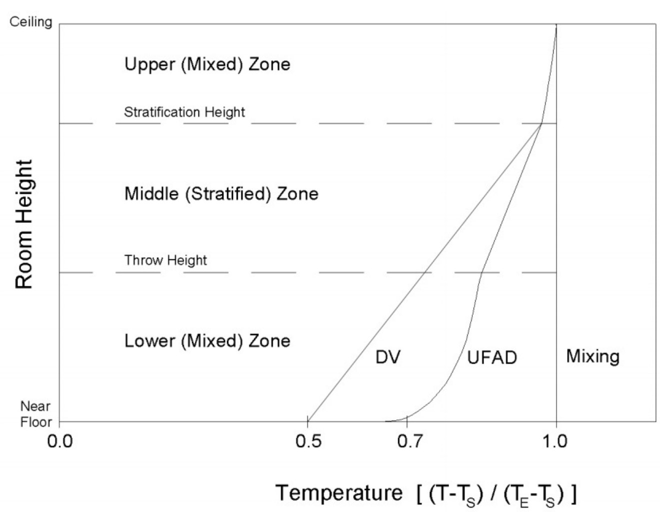


Figure 2. Vertical temperature profiles for displacement ventilation, underfloor air distribution, and mixing systems (ASHRAE, 2013b)

It can be seen from Figure 2 that UFAD system has a unique temperature profile; three distinct zones in the room may be used to represent the room air diffusion. However, the profile can vary significantly depending on several control factors such as room height, momentum of supply air, and design of supply outlets.

2.2 Supply Air Flow

In general, the main equipment used in UFAD systems (such as air handling unit) is similar to conventional OH systems. But, to avoid causing thermal discomfort in the OZ, the supply air of an underfloor system is usually delivered at a higher temperature (16-17ºC) than a conventional OH system (12-13ºC). This can increase energy efficiency of the air-conditioning system by extending the hours that the building can be "free-cooled" with outside air, also known as airside economizer (Hui and Li, 2002; Xue and Chen, 2014). For warmer climates where solar loads can be an issue at the perimeter zone near the building envelope, a hybrid system design combining UFAD and ducted air supply might be used to provide higher velocity perimeter cooling (Pasut, Bauman and De Carli, 2014).

It is important to consider the supply air volumes and airflow patterns of UFAD systems during partload operation. Under the low to intermediate supply air volumes, the performance of an UFAD system resembled that of DV and may inherit some of the benefits of displacement systems like high ventilation effectiveness. When the supply air volume increases, the throw height of the supply outlets and the momentum of the supply air may affect the air stratification by inducing more air mixing or even completely eliminate the middle stratified zone. This situation is quite complicated and difficult to predict. Depending on the system design configurations, the air flow patterns and related thermal heat transfer in the space may vary and this must be considered in the load estimation and system operation.

3. Design Configurations of UFAD Systems

In practice, UFAD systems have a wide variation of options for design configurations when they are applied to commercial buildings (Hui and Li, 2002). For example, the system designers may consider different options and arrangements for underfloor plenum pressurization, plenum configurations, air-handling system configurations, perimeter system design, outdoor fresh air supply, diffuser types, and return air paths (ASHRAE, 2013b). Some of the configurations have significant impact on the thermal heat transfer and cooling load properties in the space. Lian and Zhang (2003) pointed out that different constructions of a room cause different cooling loads at each hour as regard to the same influencing factor and the effect of radiant heat distribution must be evaluated carefully to determine the cooling load of UFAD systems. If the system is designed properly and the best setting can be applied, it can help decrease the cooling demand of the system and enhance the energy efficiency (Alajmi, Abou-Ziyan and El-Amer, 2013; Alajmi and El-Amer, 2010).

3.1 Typical Design Configurations

Table 1 shows the typical design configurations of UFAD systems. It should be noted that simply putting an UFAD system in a building without proper design and control will not provide the building owner the desirable effects. To optimise the system performance, it is essential to understand the effects of the design configurations and evaluate them on the thermal and energy characteristics.

Table 1. Typical design configurations of UFAD systems

Description	Options
Underfloor plenum pressure	• Positive pressure (typical 12 to 25 Pa) • Zero pressure (fan-power outlet is needed) • Negative pressure (typical -5 to -12.5 Pa)
Underfloor plenum design	• Series plenum • Reverse series plenum • Common plenum • Parallel (zoned) plenum
Air handling unit (AHU)	• With central AHU for supply air • With central primary air unit for fresh air only • With decentralised AHU (located in conditioned space)
Outdoor fresh air supply	• By central AHU or fresh air fans • By decentralised fresh air fans
Supply air outlets	• Passive floor diffusers (need pressurized plenum) • Fan-powered terminals • Devices in furniture or partitions (such as task air-conditioning)
Supply air design	• Constant flow • Variable flow (proper control is required)
Air duct arrangement	• Complete ductless design • Use air duct in main distribution route only • Use air duct in some branch distributions • Full use of air duct in underfloor plenum
Perimeter zone	• Use the same approach as interior zone • Combine UFAD with ducted systems • Combine UFAD with other terminal devices
Free cooling or air economizer	• Do not apply free cooling • Free cooling with temperature or enthalpy control
Return air path	• Through ceiling plenum only • Through ceiling plenum and floor return grille • Through floor return grille only • Through sidewall return inlets or via corridor

In principle, from the viewpoint of airflow pattern, UFAD systems can be designed with different arrangements of return and exhaust paths. For example, Figure 3 shows four different combinations of the paths as studied by Xu, Gao and Niu (2009):

(a) Floor supply, floor return and exhaust
(b) Floor supply, ceiling return and exhaust
(c) Floor supply, floor return, ceiling exhaust
(d) Floor supply, middle return, ceiling exhaust

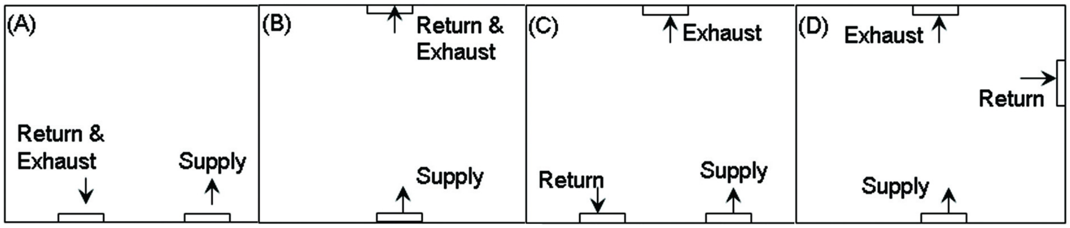


Figure 3. Different combinations of UFAD systems (Xu, Gao and Niu, 2009)

To benefit from the thermal stratification, the UFAD system may be designed so that a portion of heat gains in the space can be excluded when estimating the space cooling load. This heat gain can be taken away by the return/exhaust air flow. The cooling load reduction depends mainly on the vertical location of the return/exhaust grilles and the split of the radiant and convective components of the heat sources (Xu, Gao and Niu, 2009).

3.2 Hybrid and Integrated Design Solutions

Sometimes, hybrid design solutions may be considered for UFAD systems to achieve better cost saving and to meet the specific needs of the application. For example, Carrier Corporation (2003) suggested that in high-load and variable-loaded zones, such as perimeter zones, UFAD can be used in conjunction with traditional OH systems. Pasut, Bauman and De Carli (2014) investigated the use of ductwork (flexible or rigid) within the underfloor plenum to deliver cool air specifically to perimeter zones or other critical areas of high cooling demand. This hybrid system design combining UFAD and ducted air supply can help overcome the temperature rise problem of the underfloor plenum due to excessive heat gains from the concrete slab and the raised floor panels.

In addition, integration of UFAD with other HVAC systems may improve the overall system performance. For instance, Strapp (2012) found that by working with a UFAD system, an in-floor chilled beam can deliver chilled water to the perimeter space of a building for high energy efficiency and good overall building performance. Also, Raftery, *et al.* (2012) indicated that an integrated UFAD and radiant hydronic slab system can improve occupant thermal comfort and reduce thermal decay issues in the underfloor plenum. Moreover, Zhang, *et al.* (2014) found that liquid desiccant system is very suitable to integrate with UFAD system for dehumidifying as the maximum air velocity in the UFAD system is commonly lower than 2.0 m/s.

In areas where buildings have both heating and cooling loads, the heating loads usually cannot be served only with warm air through the air-handling units via UFAD systems. Zukowski (2006) found that cooperation of the underfloor warm air distribution system with a heat recovery unit and low-temperature energy sources can provide a high efficiency solution for space heating. Also, a combination of radiant technology and warm air heating can be used as an alternative to the conventional hot water heating in the residential houses. In general, the calculation of heating loads for UFAD systems can use the same methods as for conventional OH systems; the perimeter heating loads are calculated by adding up the skin heating loads, the heat conducted through the raised access floor in the perimeter zone, and any minimum ventilation heating load.

4. Cooling Load Characteristics of UFAD Systems

Cooling loads for a building with a UFAD system are often estimated in much the same manner as for a conventional OH system but with a few differences (Bauman, 2003; Carrier Corporation, 2003). For a ceiling-based OH system, the OZ is effectively floor-to-ceiling, because the space is well-mixed (Filler, 2004). In UFAD system, the space is divided vertically into two zones, an OZ (about 1.8 m) extending from the floor to head level, and an unoccupied zone extending from the top of the OZ to the ceiling. In principle, the UFAD system is designed to condition the lower OZ only; temperature and environmental conditions in the upper zone are allowed to float above normal comfort ranges. Figure 4 shows the space heat gains and vertical zones of UFAD system. Table 2 indicates the typical components of space heat gains and cooling load. While the individual space heat gains encountered in UFAD systems differ little from those in mixed-air OH systems, the cooling requirements of the space may vary considerably (ASHRAE, 2013a, Chapter 20).

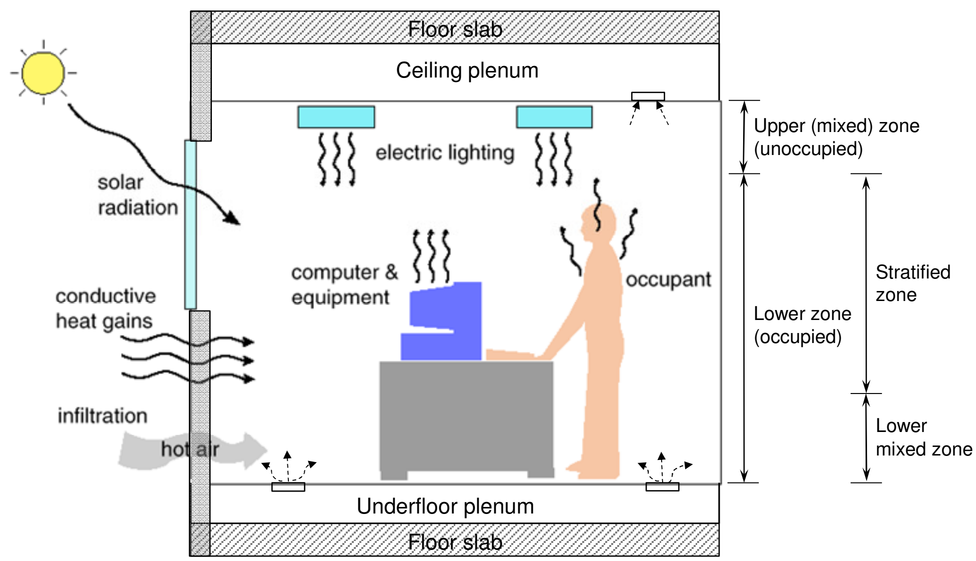


Figure 4. Space heat gains and vertical zones of UFAD system

Table 2. Components of space heat gains and cooling load

Description	Components
External	• Heat gain through exterior walls and roofs • Solar heat gain through fenestrations (windows and skylights) • Conductive heat gain through fenestrations • Heat gain through partitions, interior doors, ceilings and floors
Internal	• People • Electric lights • Equipment and appliances
Infiltration	• Air leakage and moisture migration, e.g. flow of outdoor air into a building through cracks, unintentional openings, normal use of exterior doors for entrance
System (HVAC)	• Outdoor ventilation air • System heat gain, e.g. duct leakage & heat gain, reheat, fan & pump energy, energy recovery

4.1 Thermal Stratification

The fact that conditioned air in UFAD system is delivered at or near floor level, creates thermal stratification which results in most convective heat gains (Carrier Corporation, 2003). The phenomenon of thermal stratification leads to the natural buoyant transfer of convective heat plumes that form above the mixing level of the space to the upper level, where their heat can be removed with return or exhaust airflow. Whether the thermal stratification is achieved and what the value of stratification height is can determine the percentage of convective heat gains that escape naturally without influencing thermal comfort. Therefore, only those that are captured within the OZ or otherwise affect the thermal comfort will be considered during cooling load calculation. Heat sources must be analyzed based on their convective and radiative components. Depending on the location of the heat source in the space, some amount of the convective portion can be neglected in this calculation. Lighting load is one such example.

In principle, all of the transmission and infiltration that occurs above the OZ can be transferred directly to the return air and they will not affect the space cooling load (York International Corporation, 1999). In an OH system, solar radiation penetrates the space, warms the concrete slab and is then radiated back into the space. With a UFAD system, the solar radiation that penetrates the space warms the raised access floor. A portion of the heat becomes a space sensible load and the other portion conducts into the supply air plenum. The portion that conducts into the supply air plenum does not become part of the space load. Also the heat from conduction, infiltration, and solar radiation warms the air adjacent the skin which convects upward warming the return air and a significant portion does not become a space load.

4.2 Temperature Rise in Supply Plenum

Cooling supply air flowing through the underfloor plenum is exposed to heat gain from both the concrete slab and the raise floor panels (ASHRAE, 2013b). Therefore, a temperature rise of supply air can be seen due to the long resident time of supply air and the absence of thermal insulation on the slab surfaces. Lee, *et al.* (2012) found that several parameters influenced the temperature gain in the plenum, including central air handler supply air temperature, zone orientation, floor level, climate, interior load, and plenum configuration. Xue and Chen (2014) discovered that the airflow and air temperature distribution in the floor plenum can be highly non-uniform. The variation of supply outlet temperature can vary widely in a UFAD system and must be considered during load calculation. Most of this heat transferred through the floor into the supply air stream will re-enter the conditioned space, although not instantaneously due to the mass of the floor panels (York International Corporation, 1999). This adds another component to the space cooling load calculation (estimated to be as high as 10 W/m^2). This portion can be subtracted from the space sensible load during the cooling load estimation.

Schiavon, *et al.* (2010) found that the installation of a raised floor system in commercial buildings can change the thermal behaviour of the building by reducing the interaction between the heat gains and the thermally massive concrete slab. They have shown that the mere presence of the raised floor largely affects the zone cooling load profile and the peak cooling load over the range of −7 to +40%. The most significant parameters are the zone orientation, i.e. the exposure to direct solar radiation, and the presence of floor carpeting.

4.3 Possible Ways to Reduce Cooling Load

By proper integration of a UFAD system into building structure, it is possible for the overall height of service plenums (underfloor and ceiling plenums) to be reduced in the building design (Hui and Li, 2002). It can be seen that a reduction of 400 mm can be achieved by integrating the UFAD system. If the building floor-to-floor height is decreased as compared with a building using the conventional OH system, the total amount of heat gains from the building envelope and the respective cooling loads can be reduced. The effect is particularly large in buildings and spaces with higher ceilings, such as theatres and indoor stadiums.

For buildings with intermittent operation (such as office buildings), the HVAC system is shut down at night and during holidays. With a proper control strategy, it is possible to achieve energy and operating cost savings by using the concrete floor slab in a thermal storage strategy and by night venting of the floor plenum (Yang and Li, 2008). To optimise this effect for different climatic regions, the relationship between thermal mass and cooling load of the building must be studied carefully. For the most effective reduction of cooling load, the interior and exterior convective heat transfer numbers need to be matched. Together with the control method of night thermostat setback, it is possible to take advantage of the underfloor plenum in UFAD systems (with large areas of exposed internal thermal mass) to promote the passive ventilation.

5. Cooling Load Calculation Methods

Loudermilk (1999) pointed out that most load calculation procedures and computer programs in use today are based on OH systems, and they do not provide the designer the tools necessary to properly assess the UFAD systems. To overcome these problems, research studies have been conducted in the past decade to develop and improve the cooling load calculation for UFAD systems. Specific calculation methods and simplified design tools have been set up for this purpose. New modules on UFAD systems have also been developed in some building energy simulation software.

5.1 Current Methods

Yong and Ye (2008) compared and analysed the cooling load calculation methods for UFAD systems and recommended that designers should select calculation methods according to the floor height, characteristics of cooling load, HVAC system mode and air supply mode in UFAD system design. If the supply air flow rate is small and the UFAD air flow pattern is similar to DV, then the cooling load calculation method for DV may be used, such as Chen and Glicksman (2003). On the other hand, if no thermal stratification is found during the UFAD system operation, the conventional OH method may be applied but the heat transfer from the space air to underfloor plenum should be deduced.

Lian and Zhang (2003) found that the distribution ratio of radiation heat on each inside surface of building enclosure of a room has an important effect on the accurate calculation of cooling loads. This finding agrees with other researchers (Bauman, 2003; Bauman, *et al.*, 2007) and provides the basis for developing the current methods of cooling load calculation for UFAD systems. Table 3 gives a summary of the cooling load calculation methods for UFAD systems. They were established by using either correction coefficients or load ratios of UFAD and OH systems (Zhang, *et al.*, 2014).

Table 3. Cooling load calculation methods for UFAD systems

Name and Source	Description
Loudermilk's Method (Loudermilk, 1999)	A method separating the conditioned space into two zones: a mixing zone with the lower (occupied) zone of the space and displacement-type flow in the upper (unoccupied) zone.
York's Method (York International Corporation, 1999)	Developed by York for their FlexSys UFAD system. This method indicates that only a portion of the sensible heat generated in the space should be assigned directly to the return air or cooling coil. It is suggested that 20% of the overhead lighting and 60% of the building envelope load should be included in the cooling load calculation. An extra 6.5 W/m^2 should be subtracted due to the influence of the raised access floor system.
Carrier's Method (Carrier Corporation, 2003)	Similar to Loudermilk's Method, it separates the space into two zones and assign loads to the upper stratified zone.
Lian and Ma's Method (Lian and Ma, 2006)	A practical correction coefficient method based on two traditional approaches including cooling load function and harmonic response. Either partial or integral correction can be applied to the results of traditional OH method.
Load Ratio Method (Bauman, Webster and Benedek, 2007)	A spreadsheet-based calculation procedure to apply the room cooling load ratio (RCLR) to the results of a standard OH load calculation and determine the cooling design airflow from empirical correlations.
CBE UFAD Design Tool Method (Schiavon, et al., 2011)	An updated and more complete version of the load ratio method. Transform the cooling load results of conventional OH system into that of UFAD system by splitting the total load into three portions: supply plenum fraction (SPF), zone fraction (ZF) and return plenum fraction (RPF).

5.2 Building Energy Simulation Software

It is now very common for building designers to use building energy software to perform cooling load calculations and building energy analysis. In order to model UFAD systems and analyse their energy performance using typical building energy simulation programs (like eQUEST and EnergyPro) which have no explicit UFAD models, one possible method is to artificially assign a portion of the heat gains from people, lights and equipment from the conditioned space directly to the return air through an unconditioned (ceiling) plenum space (EDR, 2012). This approximation method can help determine the design cooling load as well as building energy consumption by using the more familiar and currently available simulation software. But the assignment of the heat gains is usually based on experience or perception.

To further improve the simulation analysis, some researchers have developed a UFAD module in the building energy simulation software EnergyPlus (Bauman, *et al.*, 2007; Lin and Linden, 2005). This has enabled design practitioners and researchers to model the energy performance of UFAD systems accurately and to compare them with that of conventional systems (Alajmi, Abou-Ziyan and El-Amer, 2013). This UFAD model is also used as the basis for another simulation software TRACE 700 to run the UFAD load calculations. However, as EnergyPlus is a complex software and requires much time and effort to operate, it is more practical to develop simplified load calculation tools for practitioners to use (Chen, 2014).

5.3 Simplified Design Tools

Currently, there are two simplified design tools for UFAD systems. The first one is a spreadsheet-based tool named the CBE UFAD Cooling Load Design Tool, developed at Center for the Built Environment (CBE) at University of California, Berkeley (Schiavon, *et al.*, 2010 & 2011). This CBE tool also has an online version (www.cbe.berkeley.edu/research/ufad_designtool.htm). The other one, named the RP-1522 tool, was developed at Purdue University as result of the ASHRAE Research Project (RP-1522) (Xue, *et al.*, 2012). These tools allow the use of a familiar load calculation procedure for mixing OH systems as input for the UFAD cooling load calculation. The designer can transform the cooling load results of conventional OH system into that of UFAD system easily by splitting the total load into three portions according to the heat transfer pathways: supply plenum fraction (SPF), zone fraction (ZF) and return plenum fraction (RPF). Figure 5 shows the concept of the calculation of the CBE tool. UCLR is the UFAD cooling load ratio to compare the cooling load calculated for a UFAD system to that for a well-mixed system.

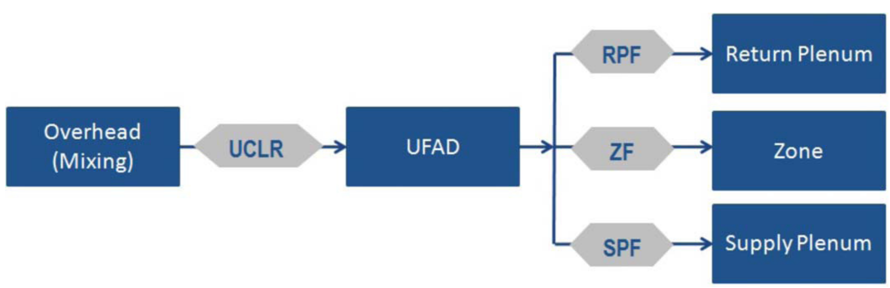


Figure 5. CBE simplified UFAD cooling load design tool (Schiavon, et al., 2011)

Chen (2014) pointed out that the CBE tool can predict the UFAD cooling load, calculate heat gain in the supply plenum, model different plenum configurations and zone types. But it has the limitation of primarily being used in office buildings and not able to calculate air distribution effectiveness. Also, it is often inflexible in changing the dimensions of the indoor spaces to be studied. The RP-1522 tool covers more buildings types and is able to calculate the air distribution effectiveness. However it requires users to input the zone cooling load, supply plenum factor and the supply airflow rate of each diffuser, which is difficult to get during the design stage for UFAD system. After comparing the two UFAD design tools, Chen (2014) has also updated the CBE tool with new stratification models and extended capabilities.

6. Discussions

Although in recent years some cooling load calculation methods, simplified design tools and building energy simulation models have been developed for UFAD systems, they still have many limitations and most building designers are not familiar with them. It is important to promote them and integrate the knowledge into the main-stream practice of load calculation and HVAC design for building designers. It is also essential to improve the calculation methods to cater for different design configurations and applications of UFAD systems.

6.1 Integration into the Main-stream Practice

The fundamental principles and scientific methods of cooling load calculations can be found in the references, such as ASHRAE (2013a, Chapters 15-18) and Spitler (2010). At present, several numerical methods can be used for the load estimation and all of them are established based on OH mixing systems. These methods include:

(a) Heat balance (HB) method
(b) Radiant time series (RTS) method
(c) Transfer function method (TFM)
(d) Cooling load temperature difference/cooling load factor (CLTD/CLF) method
(e) Total equivalent temperature difference/time average (TETD/TA) method

The HB and RTS are the newer methods with a direct approach and less dependency on subjective inputs; the TFM, CLTD/CLF and TETD/TA methods are still valid and commonly used for many applications and load calculation software. When UFAD systems are evaluated using these methods, the cooling load calculation procedures are similar to those for conventional OH systems. For example, for the TFM, the enclosure, heat sources, and indoor air can be considered as a linear system in the UFAD design; the heat gains produced by the heat sources are taken as the disturbance to the thermal system. However, the design configurations and system characteristics as described in the previous sections must be studied carefully to determine appropriate assumptions for the load estimation and assess possible variations of the key parameters of UFAD, such as vertical temperature, heat flow paths, and thermal storage.

The system design guidance and principles described in ASHRAE (2013b) will be useful for building designers to consider their UFAD design arrangements before conducting the cooling load calculations. In order to reduce the cooling load and optimise the system performance, it is important to examine the cooling load components critically and design suitable configurations and control strategy for the UFAD system for that application. More often than not, a balance or compromise among different design requirements should be achieved for the final design solution.

6.2 Improve the Calculation Methods

As UFAD can provide partially mixed room conditions and flexible air supply, the system can be designed in many innovative ways and integrated with other HVAC and building systems. This can offer new opportunities to enhance the thermal behaviour and energy performance of buildings. In order to perform the load estimation and energy analysis for the hybrid and integrated design solutions, it is necessary to review and improve the current UFAD calculation methods. For example, the integration of UFAD systems with radiant cooling and task air-conditioning will affect the heat gain components and air flow patterns. Adjustments to the heat gain distribution will be needed to represent the actual condition. The interactions among the space cooling load, space heat extraction rate and cooling coil load should be evaluated as well.

In addition, the enhancement of the UFAD model and its capability in EnergyPlus, TRACE 700 and other building energy simulation programs is essential to keep abreast of the technology development and new research findings on UFAD systems. To optimise the UFAD system performance, it is important to analyse the cooling load profiles and assess the energy efficiency strategies for different types of UFAD systems and design configurations. Moreover, the UFAD simplified design tools should be verified for use with high-ceiling spaces (such as auditoriums and theatres).

7. Conclusions

The potential benefits of UFAD system have been identified in many research studies but the application of the system is still obstructed by the information gap in some fundamental issues, such as cooling load calculations for different design configurations. It is found that room air stratification and underfloor supply plenum are two main characteristics in load calculations for UFAD systems. Although some cooling load calculation methods, simplified design tools and building energy simulation models have been developed for UFAD systems, they still have many limitations and most building designers are not familiar with them. It is discovered that thermal stratification, management of solar and lighting loads, architectural design and thermal properties of structural floor slab will influence the cooling load and must be evaluated carefully.

It is understandable that a new HVAC system like UFAD will take some time to establish and be accepted. With the efforts of many researchers in the world in the past two decades, the information gap has been partly filled. It is believed that better knowledge will be available for the effective design, analysis and implementation of the systems.

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