General

Originally UFAD systems were for computer rooms. The design intent was to cool and provide easy access to computer equipment and cabling while occupant comfort was secondary.

This document provides application and design highlights for UnderFloor Air Distribution (UFAD) systems used in occupied spaces.

Additional information regarding underfloor systems may be found online at the Titus website - https://www.titus-hvac.com.

Introduction

In 1997 Titus introduced the TAF-R diffuser and the TAF-G grommet, which were installed in the Owens Corning World Headquarters. Since then, Titus, ASHRAE, and the engineering community have continued to learn about UFAD systems. In the time that Titus has participated in UFAD designs in the US, we have continued to introduce new products to meet the needs of this unique application.

Overview

ASHRAE's Handbook Applications (2015) classifies Underfloor Air Distribution Systems (UFAD) as a "Partially Mixed" room air distribution strategy. Traditional ceiling or high sidewall based supply outlets condition the space by creating a mixing zone throughout the entire space. This results in temperatures and respiratory contaminant levels that are consistent throughout the occupied zone. Figure 1 illustrates a space served by a UFAD system. Underfloor air distribution systems create a mixed zone of limited height within the occupied zone while allowing the upper regions of the space be thermally stratified. The height of this mixed zone is determined by the height at which the supply air jets are reduced to a velocity of around 50 fpm. Heat gains and contaminants that originate above the mixed zone rise naturally through the stratified zone and pool near the ceiling. The transport of these heat gains and contaminants is accomplished by natural convection due to the increased buoyancy of the warm air, thus supply air is not needed to convey them. The heat and contaminants are then carried out of the room through return inlets which are always located above the occupied levels of the space.

A typical application for a UFAD system is the open plan office. The UFAD diffuser manufacturer defines the distance (defined as the "clear zone") that needs to be maintained between their diffuser and a stationary space occupant in order to achieve the ASHRAE recommended temperatures and velocities. Floor space is at a premium within work cubicles so a smaller "clear zone" area around the diffuser will allow more usable space in the cubicle. Thermal comfort criteria and clear zones are further discussed in subsequent parts of this Guide.

The key performance factor in UFAD systems is thus the ability of the access floor diffuser to rapidly mix room air into the supply air parcel so that the temperature and velocity of the supply air is quickly reduced to ASHRAE recommended levels.

While the early interest in UFAD systems was primarily due to companies' need to easily rearrange office layouts, information and communications based offices, the economics of ownership, and green building programs such as LEED have largely influenced the growth of UFAD.

ASHRAE has published a UFAD Guide which addresses all phases of UFAD system design, construction, operation and maintenance. It is available in the ASHRAE on-line bookstore.

UFAD and LEED v4

The United States Green Building Council (USGBC) developed the Leadership in Energy & Environmental Design (LEED™) Green Building Rating System™. The LEED council is a voluntary, consensus-based national standard board for developing high-performance, sustainable buildings. USGBC members represent all segments of the building industry and update the program continuously. Table 1 shows the LEED v4 credits that may be achieved using UFAD systems.

EA CREDIT: OPTIMIZE ENERGY PERFORMANCE

The intent of this credit is to reduce the energy usage of the building below the ASHRAE Standard 90.1-2016 prerequisite requirements.

There are two methods of achieving this credit. The first, and currently most common, method is based on percentage of energy reduction and range from 5% reduction (1 Point) to 50% reduction (18 Points) for new construction. Two additional points can be achieved for healthcare buildings. The percent reduction is determined by completing a whole building energy simulation.

The second method of achieving this credit is to comply with the Prescriptive Compliance Path in the ASHRAE Advanced Energy Design Guides[5]. Using this method, you can achieve up to 6 points.

EQ CREDIT: THERMAL COMFORT

The intent of this credit is to promote occupant productivity, comfort and well- being by providing quality thermal comfort. LEED v4 awards credit for buildings whose HVAC systems comply with ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy[6] and provide individual thermal comfort control for at least 50% of their individual occupant work spaces.

UFAD Design Basics

THERMAL COMFORT CONSIDERATIONS IN UFAD SYSTEMS

ASHRAE Standard 55-2017 defines the ***occupied zone*** as the portion of the space which is a) no closer than one meter (3.3 feet) from and outside wall or window, b) no closer than one foot (0.3 m) from an inside wall and whose height is determined by the head level of the predominant space occupants. In the past, an occupied zone height was often considered as 5.7 feet (1.7 m) but for seated occupants a height of 3.5 feet (1.1 m) is more appropriate.

The Standard specifies the combinations of occupied zone environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space. The environmental factors addressed in the standard are temperature, thermal radiation, humidity, and air speed; the personal factors are those of activity and clothing.

It has been shown that individual comfort is maintained when the following conditions are maintained in a space:

- Air temperature maintained between 73-77°F (23-25 C)
- Relative humidity maintained between 40 and 60%
- Vertical temperature gradients between the occupant ankle and neck levels should not exceed 5.4°F (3 C)

ASHRAE Standard 55-2017 (section 5.3.3.4) suggests maximum local air speeds for varying operative temperature levels shown in table 2 below.

CRITERIA CLASSIFICATION	POINTS
ENERGY & ATMOSPHERE	
Optimize Energy Performance	Up to 20
INDOOR ENVIRONMENTAL QUALITY	
Thermal Comfort	1

Table 1: LEED v4 Credit Opportunities with UFAD Systems

The following table lists abbreviations used within this document.

Abbreviation	Term
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
UFAD	UnderFloor Air Distribution
LEED	Leadership in Energy & Environmental Design
USGBC	U. S. Green Building Council
CBE	Center for the Built Environment Cal Berkeley

OPERATIVE TEMPERATURE, °F	MAXIMUM AIR SPEED, FPM
72	40
73	40
74	41
75	57
76	85
77	125
78	160

Table 2: Maximum local air speeds for various operative temperatures

When supply air is introduced directly with the occupied zone, as is the case with UFAD and most displacement ventilation applications, areas where velocities and temperatures that are outside these limits are known to exist must be identified and observed when locating stationary occupants. Areas within the occupied zone where velocities exceeding 50 fpm (0.25 m/s) are likely to exist are referred to as "clear zones". Manufacturers' literature should clearly identify both the horizontal expanses of the ***"clear zone"*** with respect to center of their outlet. It is recommended that occupants not be permanently stationed within the outlet's clear zone.

VENTILATION EFFECTIVENESS

ASHRAE Standard 62.1-2016 quantifies the volume flow rate of outside air required for a given building space. Table 6-2 of the Standard shows zone ventilation effectiveness (E_z) factors for various supply outlet locations and types. Displacement ventilation systems are awarded a factor of 1.2. The table also awards UFAD systems with supply outlets whose vertical terminal velocity does not exceed 50 fpm lower when measured 4.5 ft. above the floor, the same (1.2) ventilation effectiveness. When the supply air jet velocity exceeds 50 FPM at the 4.5 foot height, the zone ventilation effectiveness factor (1.0) is assigned.

UFAD systems should always employ return inlets that are located several feet above the head level of the space occupants to assure that the respiratory contaminants are removed from the space and not recirculated back to the occupied zone. The sizing of these returns should be ample due to the low operating pressures of the system.

UFAD SUPPLY AIR PLENUMS

UFAD systems utilize the cavity beneath the raised access flooring system as a conduit for supplying conditioned air to the space. Raised access floors are generally employed when considerable changes in the space are expected to occur. The raised floor system allows easy access space to modular power, voice and data services that allow them to be easily reconfigured to accommodate these changes. The fact that the HVAC system shares this space with those other services makes it critical to limit and locate HVAC components such that they don't impact the flexibility of those other services.

The pressurized plenum is essentially a large duct maintained at a constant pressure differential to the room above; typically between 0.05 and 0.10 in. pressure (w.g.). Plenum heights typically range from 12" to 18", largely dependent on the height of the HVAC components within them.

Plenum pressure is maintained through the supply of conditioned air via one or more supply air distribution points. The spacing and location of these are dependent on the space airflow requirements and the plenum depth, with shallow plenums and/or high airflow quantities requiring more air supply air points under the floor. UFAD supply air diffusers are usually tapped directly into the supply air plenum but may also be ducted, and often fed by a fan assisted zone airflow terminal.

As a general rule, the maximum distance from any diffuser to a supply air discharge point into the pressurized plenum should not exceed about 30 feet. Distances longer than this are subject to significant thermal degradation of the supply air due to heat transfer through the slab as a result of the warm return air from the floor below. Duct runs within the supply air plenum space known as ***"air highways"*** are often used to transport conditioned air from the main duct to these remote points of discharge into the pressurized plenum.

If zone separation is desired within the underfloor plenum, the plenum can also be partitioned into separate zones. The zones in the underfloor plenum should correspond to building zones having similar load requirements. The use of air highways and partitioned plenums, however, often complicate future relocation of power, voice and data cabling and as such should only be employed where absolutely necessary. If an office layout must be changed, the partitioned plenums will need to be changed to match the new layout.

PLENUM LEAKAGE

Sealing the underfloor plenum is critical to the proper operation UFAD systems.

Leakage that occurs from the plenum through vertical walls in the plenum is referred to as Type I leakage. This leakage results in conditioned air short circuiting back through the building return pathway without performing its desired space conditioning and should be minimized. Care should be taken to inspect and seal all openings into the walls where electrical, plumbing, conduits or other items may pass from the pressurized plenum.

Conditioned air leakage between access floor tiles and that associated with floor based service outlets (commonly referred to as type II leakage) passes through the occupied space and thus compliments the cooling of the space. While leakage through the floor tile seams into the occupied space is less critical it should not be ignored. Excessive vertical leakage can compromise the UFAD system's ability to respond to space load changes and result in overcooling of the space. Acceptable floor sealing can usually be achieved by using carpet tiles that overlap the seams between the floor tiles. Floor leakage can be minimized by applying a gasket between the floor tile and the support stringer. Type II leakage of approximately 5% of the plenum design airflow rate when pressurized to 0.05 inches (12 Pa) water gauge is reasonably attainable[2].

The surfaces of UFAD plenums are usually constructed by other trades that are not generally familiar with how airtight the plenum must be to support the HVAC services to the space. It is recommended that regular inspections of these plenum surfaces be performed by an HVAC professional ***prior to the installation of the access floor tiles*** to assure that adequate sealing has been achieved. Failure to achieve this can lead to insufficient plenum pressurization and costly repairs after the floor has been installed.

PLENUM HEAT TRANSFER EFFECTS

Providing sufficient cooling to perimeter areas is typically the most challenging part of underfloor system design. Perimeter cooling loads are typically much greater than those encountered in interior areas. In addition, perimeter spaces encounter load changes that vary in frequency and magnitude due to external factors.

Heat transfer into the supply air plenum presents design challenges for UFAD systems serving perimeter areas. Solar radiation warms the first four to six feet of the raised floor as well as the slab beneath the floor. This as well as thermal conduction through the outer wall affects the temperature of the conditioned air within the plenum.

Warm air passing through the return air plenum also transfers heat through the slab and into the pressurized plenum above, increasing the supply air temperature significantly as it flows to the outer boundaries of the plenum. Figure 1 illustrates this phenomenon and its potential effects on temperatures within the plenum. The combination of heat transfer effects and the resultant diminished stratification often necessitate perimeter supply airflow rates that are often more than double those which would be required with a conventional ducted overhead system. There is often a thermal storage effect within the slab which affects the transmission and delays the impact of these heat gains which makes them nearly impossible to estimate. Every building has a unique response dependent on many factors including the building mass and orientation as well as the processes housed within the structure.

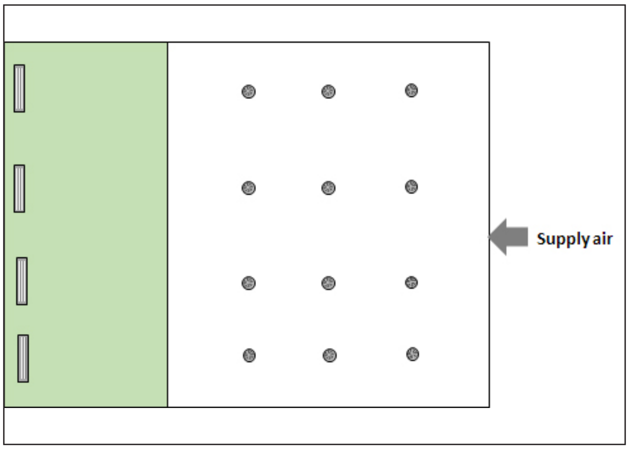


Figure 1. Series plenum configuration

ASHRAE's UFAD Guide suggests alternative plenum configuration strategies designed to reduce plenum heat transfer effects. The plenum configuration in Figure 2 is referred to as a reverse series configuration as opposed to the series plenum configuration shown in Figure 1 above. In the reverse series configuration, conditioned air remains confined in supply (either sheet metal or fabric) ductwork until it is very close to the perimeter boundaries of the plenum, minimizing its residual time in the open plenum before reaching perimeter area outlets. The air then migrates back to interior areas resulting in higher interior outlet discharge temperatures. This not only reduces the supply air temperature in perimeter zones but also raises the floor temperatures in interior spaces where complaints regarding "cold feet" are more likely to occur.

HUMIDITY CONTROL ISSUES

Another UFAD system design challenge involves the higher supply temperature used in underfloor supply systems.

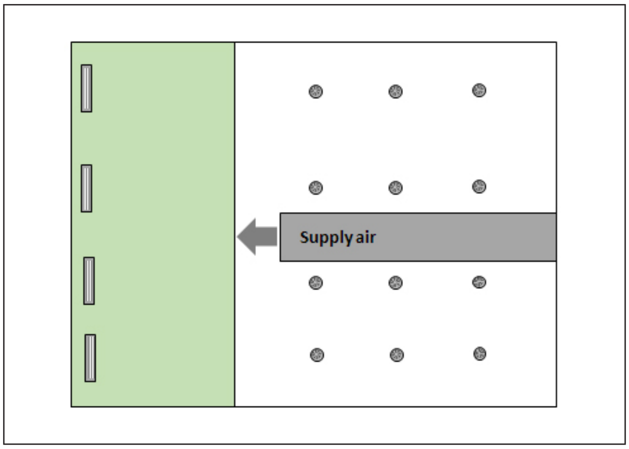


Figure 2. Reverse series plenum configuration

Since the supply air is discharged directly into the occupied zone, higher air handling unit (AHU) leaving air temperatures are usually employed. This typically results in 60 to 63°F supply air delivery to the UFAD plenum. The supply air must also maintain the room dew point temperature between 55 and 58°F to meet IAQ concerns. Room conditions of 75°F/50% RH require supply air dew point temperatures of about 51°F. Fully saturated air at 60°F has a 60°F dew point, thus the supply air must be subcooled to saturation at around 52°F to remove the required amount of moisture, then reheated before it is delivered to the room.

System designs utilizing condenser water reheat; run-around coils, face & bypass, and other strategies can be employed to solve these potential design problems. Other possible solutions include the use of a separate system to dry outside air or the use of desiccant dehumidification.

Figure 3 illustrates another method of reheating the supply air by mixing it with return air before it leaves the air handling unit. If this method is employed the moisture gain from the return air that bypasses the cooling/dehumidifying coil must be factored into the calculation of the supply air dew point dew point temperature. For example, if conditioned air is to be mixed with 55°F dew point return air and the mixture is to achieve a 50°F dew point supply to the space, the air must be subcooled to a dew point of 49°F to offset the moisture gain from the return air.

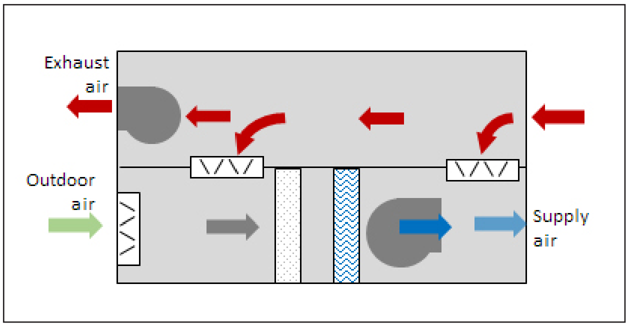


Figure 2. Reverse series plenum configuration

Climate and building operation criteria are also important considerations when designing a UFAD system. In humid climates, it may be necessary to operate the HVAC system during unoccupied hours to maintain acceptable humidity levels in the building, although this would likely be the case with conventional ducted systems as well.

CONTROL AND ZONING OF UFAD SYSTEMS

Adjacent spaces that share similar simultaneous cooling and heating loads can often be zoned together and operated off a single thermostat. The common zone types found in an office building are discussed below. In all cases, the use of terminal units, ductwork and vertical partitions should be minimized to allow easy relocation of the other space services housed in the plenum.

INTERIOR (CORE) SPACES

Interior spaces typically do not require heating nor do their occupied cooling loads tend to vary significantly. As such, high induction (swirl type) floor diffusers such as the Titus TAF-R series are typically used. The TAF-R series incorporates an occupant adjustable damper which affords the occupant control of the airflow rate entering their work zone by simply rotating the face of the diffuser. These outlets are typically placed at or near the entrance to the cubicle or individual work area to assure that the occupant does not reside within the diffuser's clear zone. Ideally, the outlet's design (fully open) airflow rate will result in a vertical throw to a 50 FPM terminal velocity that does not exceed the height of the occupants' breathing zones in order to minimize the cross transmission of respiratory contaminants and qualify for the zone ventilation effectiveness factor (E_Z) of 1.2 offered by ASHRAE Standard 62.1-2016.

The use of occupant adjusted floor diffusers also minimizes the amount of HVAC equipment within the floor plenum, making it easier to relocate the other services housed in the floor cavity.

Partitioned interior offices may also be served by these occupant adjustable diffusers or alternatively may be provided with a thermostat operating swirl type outlets with automatically controlled airflow dampers.

CONFERENCE AND MEETING ROOMS

Conference and meeting rooms often experience a widely shifting cooling demand based on their occupancy. Swirl diffusers with motorized dampers can be ganged off a single zone thermostat to automatically adjust their airflow rates in accordance with their cooling load. These dampers will also allow shut-off of their airflow rate during periods when they are unoccupied.

Demand control ventilation of these spaces can also be applied by tying a CO_2 sensor into the control loop. This will allow the supply airflow rate to be reduced when CO_2 levels permit doing so. A room controller will monitor both the temperature and CO_2 levels and reset the zone airflow based on the need to cool the space or changes in occupancy.

PERIMETER AREAS

Perimeter area cooling loads are typically 2.5 to 3 times those encountered in interior zones. Thermal decay within the supply air contributes to perimeter zone airflow requirements that can be up to six times those required by interior spaces!

Perimeter areas also experience frequent and sizable load shifts during a typical day's operation. As such, it is imperative to employ some type of automatic temperature and/or airflow control in these areas. Perimeter areas also require provisions for heating to offset the skin losses through the building façade. Heating should always be provided at the zone level by either fan terminals with integral heating coils or by fin tube elements separated from the supply air plenum. Heating the supply air that passes through the plenum will heat the slab and it will take hours after the heat is discontinued to get the slab stabilized. Conditioning of perimeter areas can be accomplished in various ways.

PERIMETER FAN TERMINALS

In the past, the most common method of conditioning the perimeter was to use fan powered terminals with reheat ducted to linear bar grilles. There are issues that accompany this design concept. The throw of a linear bar grille ducted to the discharge of a fan powered terminal is very long, possibly as long as 15-20 feet. Designing for long throws at the perimeter effectively destroys the stratification desired in a UFAD system design and increasing the airflow rate required for conditioning the space.

UFAD system fan terminals are always used to provide heating to perimeter spaces. They are capable of doing this even when the central air handling unit is off. They may also be configured to act as booster fans delivering larger volumes of cool plenum air to the space than would be possible by the pressurized plenum itself.

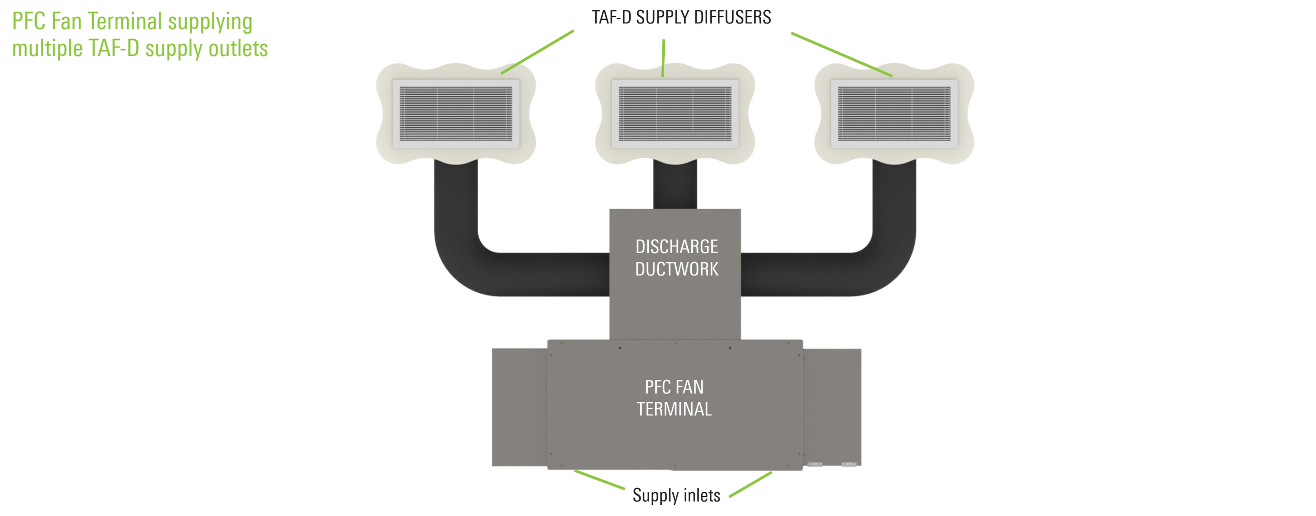
When perimeter fan terminals are employed in UFAD systems, several issues must be considered:

1) *Are the fans to be operated for just heating or both heating and cooling?*
2) *Are the fans to be constant or variable speed?*
3) *Are the heating coils within the unit to be electric or hot water?*
4) *Is the source of air for heating the plenum or recirculated room air?*

Titus offers two series of fan terminal units for use in UFAD systems. The PFC was designed to be used as a booster unit for perimeter and conference room applications. The PFC fan powered terminal unit is designed to be installed between the pedestals in an underfloor system with a floor height of 12" to 18". It can also be provided with hydronic or electric heating coils.

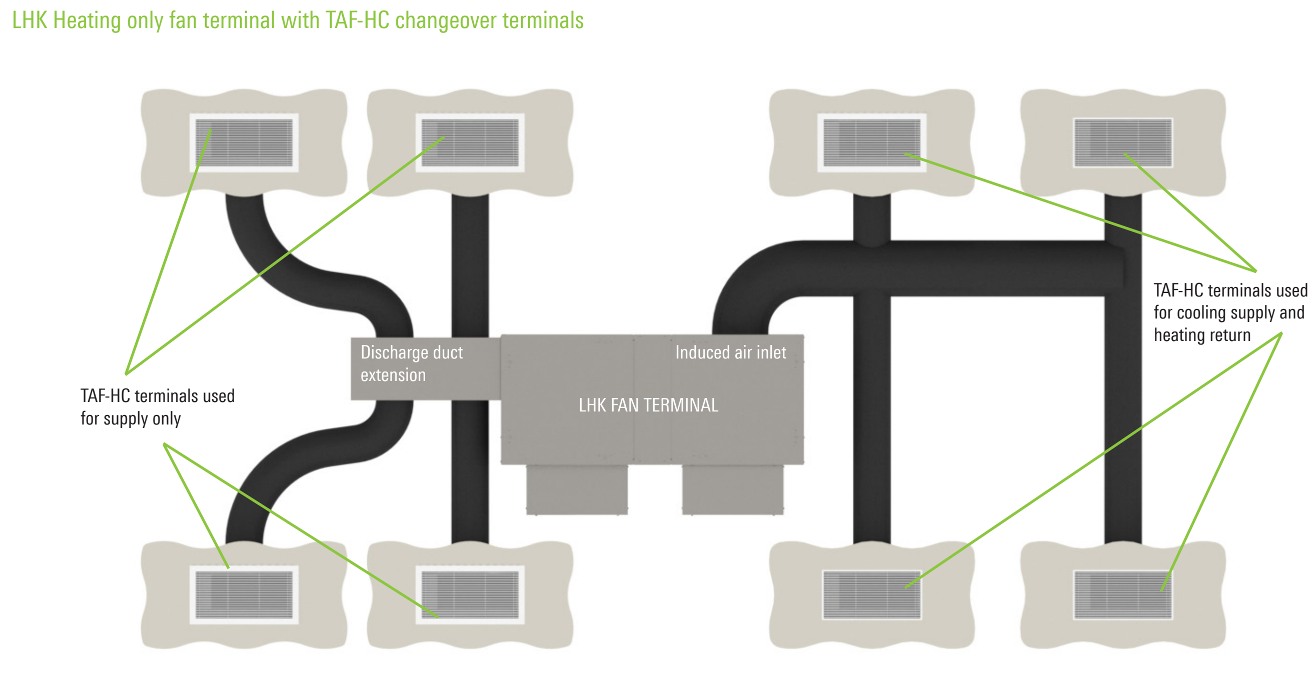
The PFC draws conditioned air directly from the supply plenum and is usually ducted to diffusers, such as CT series linear bar or TAF-D diffusers, The discharge airflow of the diffusers is usually directed toward the glass like a typical ceiling system.

When fan powered terminals are used with an under floor system, they



Note: Number of TAF-D diffusers required depends on the airflow of the PFC

Figure 4: PFC fan terminal ducted to TFD supply terminals



Note: Number of TAF-HC diffusers required depends on the airflow of the LHK

Figure 5: LHK fan terminal ducted to TFD supply terminals

are often equipped with ultra-high efficiency ECM motors. ECM motors consume less energy and can be controlled by the unit DDC controller to adjust the fan speed to the required space load conditions.

Modulating the fan speed to vary the amount of air supplied to the zone is the most common control sequence used for Titus PFC fan terminals. The PFC's ECM controller determines the speed of the fan based on zone temperature. For example, the fan would run 100% when the zone is 75°F and modulated down to 30% as the zone approaches 70°F.

Figure 4 illustrates a PFC fan terminal ducted to TFD supply air terminals. This fan terminal can be used for both cooling and heating (using plenum air as the source for both) or heating only when separate passive outlets are supplying cooling to the perimeter space.

Titus LHK fan powered terminals were designed to handle perimeter areas and conference rooms with widely varying load conditions. The LHK is designed to pull in room air when heating is required and features a pressure independent airflow damper that facilitates connection to circular ductwork or can be used to monitor and control its volume flow rate of plenum air. Like the PFC, the LHK fits within the modular pedestal systems of the raised floor and is available in various heights to fit under 12" through 18" raised floors.

Figure 5 illustrates an LHK unit used with four (4) TAF-HC terminals. TAF-HC terminals incorporate a damper which allows the unit's air volume and source to be modulated based on the space cooling or heating demand. The LHK fan in this case is to only operate when heating is required. The two terminals on the return side of the LHK serve as inlets that draw in room air when the fan is energized. When cooling is required, they block their pathway to the fan and modulate the flow of plenum air into the space. The outlets on the supply side of the fan also open to receive warm air from the LHK during a demand for heat. When cooling is required, the damper within the TFD-HC modulates the flow of cool air from the pressurized floor plenum.

PERIMETER VAV COOLING WITH FIN TUBE STATIC HEATING

Perimeter area cooling can also be accomplished by passive (non-fan assisted) air terminals. These terminals incorporate volume control dampers that modulate the flow of cool plenum air to the space based on its cooling demand. Heating is then accomplished using hydronic finned tube elements located below the access floor along the perimeter. For best results, the heating elements should be spaced intermittently and provided with an ample path for room air to replenish the heat plume rising above the heating elements.

The TAF-L-W perimeter heating terminal is a four foot long device that incorporates a CT-TAF-L linear bar diffuser and a hydronic fin tube coil to heat the perimeter using a minimal amount of supply plenum air. The TAF-L-E uses the same concept shown above to heat the perimeter with an electrically powered SCR controlled heating element.

Titus offers several solutions designed for VAV cooling operation. TAF-V high capacity modular diffusers or TAF-R swirl diffusers with thermostatically actuated dampers that modulate their plenum air delivery can be coupled with TAF-L-W (hot water) or TAF-L-E (electric) heating terminals.

The Titus TAF-L-V is a unique perimeter cooling terminal that incorporates a motorized sliding orifice plate to vary the airflow supply to the space without affecting its throw characteristics. As the airflow is reduced the damper aperture areas are reduced resulting in a consistent projection of the supply air into the space. These terminals can also be complimented by TAF-L-W or TAF-L-E heating terminals.

DECOUPLED SENSIBLE COOLING USING PASSIVE CHILLED BEAMS

An effective method of conditioning perimeter areas is to decouple most or all of the perimeter sensible cooling from the underfloor air system. Passive chilled beams (see Figure 6 below) located directly above perimeter glazing remove up to 650 Btu/h-lf of sensible heat from the space. This effectively limits the underfloor air system's responsibility to providing ventilation and latent cooling (dehumidification) to the space. Doing so typically reduces perimeter plenum airflow rates to levels similar to those of interior spaces. This often reduces the total UFAD system airflow delivery by 50 percent or more!

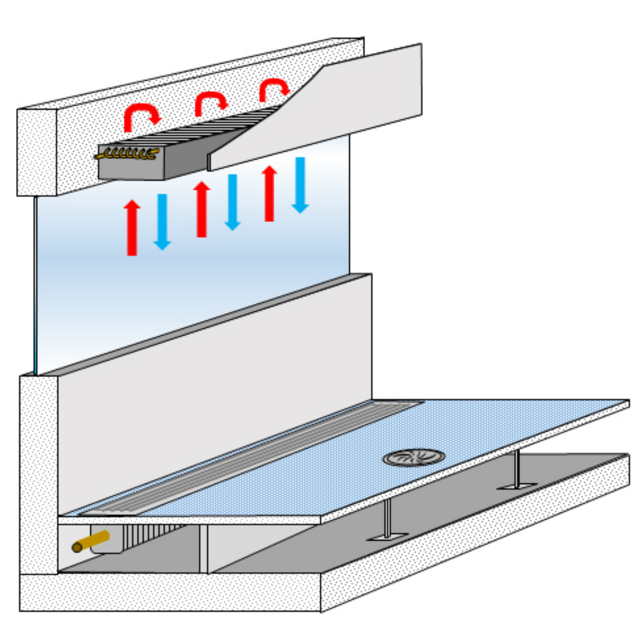


Figure 6. Passive beams for perimeter sensible cooling

When passive beams are employed, perimeter heating must be provided separately. This can be done by stopping the supply air plenum short of the façade and installing finned tube heating elements below the raised access floor. The elements would be intermittently spaced along the outside wall. A narrow linear grille would then be installed between the access floor platform and the building façade to serve as a discharge for the heated air as well as to "dead" sections where room air could fall into the trough and feed the heating elements. This method is illustrated in Figure 7 below.

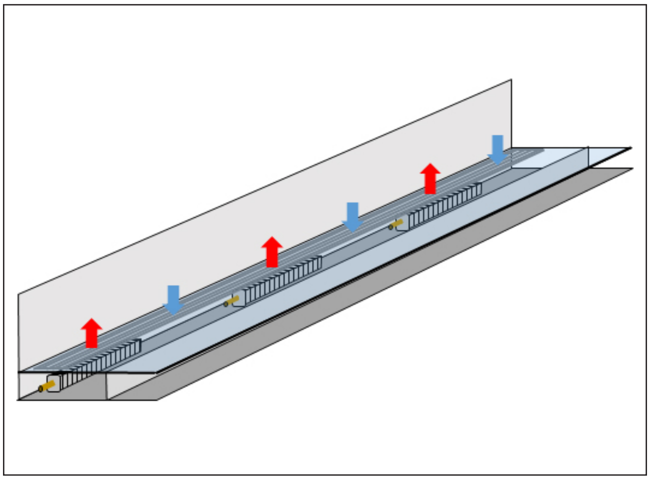


Figure 7. Underfloor trough heating

Another advantage of decoupling perimeter sensible cooling loads is that it allows the plenum supply temperature to be reset based on interior area demand. All-air perimeter cooling strategies do not allow this because raising the supply temperature would compromise perimeter area cooling capacity.

Finally, the need for plenum distribution ductwork (air highways) is virtually eliminated when decoupled sensible cooling is applied on the perimeter as rises in plenum air temperatures can be offset by the sensible cooling provided by the passive beams.

Table 3 provides a comparison of the perimeter zone treatment methods described above.

Attribute	Fan assisted cool and heat	VAV cooling, fan assisted heat	VAV cooling, fin tube heat	PCB* cooling, fin tube heat
Acoustics	High, due to fan terminal	High, due to fan terminal	Low	Lowest
Energy Use	Highest, constant fan terminal operation	Lower, fan operates only while heating	Low	Lowest
First cost	Low	Low	Moderate	Higher due to chilled water piping
Maintenance	High	High	Moderate	Lowest
Minimum finished floor height	12 to 16″	12 to 16″	10″ minimum FFH	10″ minimum FFH
Flexibility to relocate cabling	Fair	Fair	Good	Best
Plenum pressure control	Constant plenum pressure	Constant plenum pressure	Constant plenum pressure	Variable plenum pressure

**Passive chilled beams for decoupled zone sensible cooling*

Table 3: Comparison of various perimeter zone control methods

SUPPLY AIRFLOW RATE DETERMINATION IN UFAD SYSTEMS

Individual supply outlet airflow rates in UFAD systems are dependent on a) the temperature of the air when it reaches the supply outlet and b) the degree of thermal stratification that is achieved within the space. The supply airflow rates for space sensible cooling in UFAD systems can be calculated from the following equation:

$$CFM_{SUPPLY} = TSGH / 60 \ \ cP\Delta T$$

where,

TSHG = Space sensible heat gain, Btu/h
p = Density of the room air, lbm/ft^3
cP = Heat capacity of air, Btu/lbm-°F
ΔT = Temperature difference between supply and return air, °F

The vertical projection of the supply outlets used in UFAD systems has a marked effect on the supply airflow rate to the space. Rapid mixing of supply with ambient room air reduces the vertical projection of the supply jet. Mixing in UFAD systems is restrained to the volume of the space below the elevation at which the supply air jet velocities are reduced to a terminal velocity of around 50 FPM, therefore heat gains from convective heat sources located above this level escape naturally, without affecting the volume flow rate of conditioned air supplied to the space. Sensible heat that escapes in this manner increases the stratification within the space and results in higher return air temperatures which in turn increases the differential between the supply and return air temperature and reduces the required supply airflow rate.

High induction swirl diffusers (Titus TAF-R) generally require 15 to 20% less air that linear or modular types because of the lower throw heights they produce. This leads to more room air stratification and thus higher return air temperatures.

Calculation of UFAD systems airflow rates is dependent upon the accurate prediction of both plenum heat transfer effects and the room air stratification. The heat transfer affects the individual outlets' supply temperature while the level of stratification determines the return air temperature. Prediction of these temperatures is especially important when calculating perimeter area airflow rates. There are tools available that aid the designer in calculating UFAD outlet airflow rates and the number of outlets required.

The Center for the Built Environment at the University of California-Berkeley offers a UFAD cooling load and airflow calculation tool8 based on modeling using DOE's Energy Plus. The tool allows the user to develop supply airflow estimates for various plenum configuration strategies discussed in the previous section regarding plenums.

The UFAD cooling load tool can be downloaded or used online at the CBE website https://cbe.berkeley.edu/research/ufad_designtool-download.htm. The tool recognizes that cooling load profiles for UFAD systems differ from those involving fully ducted HVAC systems. As such it suggests that cooling sensible loads derived from conventional load calculation software be multiplied by approximately 1.2 when UFAD systems are applied. This multiplier is referred to as the UFAD Cooling Load Ratio (UCLR) and is largely contributed to the lower thermal storage of raised floor tiles compared to heavier structural slabs.

The tool also recognizes that this lower thermal storage capacity combined with its cooler surface temperature allows significant portion of the space heat gains to be transferred into the supply air plenum, affecting the temperature of the supply air before its point of discharge into the space. As a result the tool suggests that only 44 to 66% of the space heat gains must be removed by the supply air passing through the space. It also accounts for Type 2 leakage into the space through the raised floor surface and its components, thereby reducing the amount of air that must be supplied through the floor outlets themselves.

The tool allows the user to specify the floor type (top, middle or ground) and the size and conventional sensible cooling loads for both the interior and perimeter areas. Perimeter areas are also user classified according to their exposure and to the type of plenum configuration that is to be used. It also allows the user to designate the space occupancy as well as the type and quantity of floor outlets to be employed. The user also specifies the temperature of the supply air initially entering the UFAD plenum.

The tool then uses these data and the assumptions above to predict average discharge air temperatures for interior and perimeter zones fed by a variety of plenum configurations as described above.

Finally, the tool factors the effect of various outlet types and flow rates on thermal stratification to predict zone airflow rates for both interior and perimeter spaces.

The UFAD selection examples that follow are calculated using the UFAD Cooling Load Tool.

UFAD SELECTION EXAMPLES

Figure 8 represents a section of the middle floor of an office building that will serve as the basis for the selection examples that follow. The interior unshaded portion of the floor is 1,680 ft^2 (60 feet wide by 28 feet deep), houses 8 occupants and has a sensible cooling load of 12 Btu/h-ft^2. The

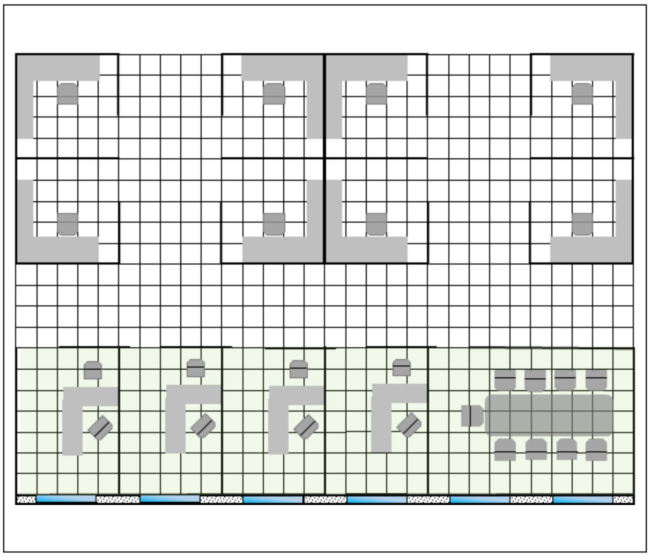


Figure 8. Floor plate layout for selection examples

interior area latent load is 1,600 Btu/h.

The west facing shaded perimeter area comprises two control zones. The first consists of four 14 x 10 private offices, is designed for a maximum occupancy of 8 and has a sensible and latent cooling loads of and 3.5 Btuh-ft^2, respectively. A 20 x 14 perimeter conference room is to be zoned separately and when fully occupied has sensible and latent cooling loads of 36 and 8 Btu/h-ft^2, respectively. The sum of the perimeter area sensible heat gains is thus 26,560 Btu/h while perimeter area latent heat gains total 3,880 Btu/h. The perimeter area net design heating requirement is 12 MBH which equates to 200 Btu/h per linear foot of perimeter.

The plenum is a series type configuration as shown in Figure 1. It is designed for a static pressure that is 0.05 inches H_2O greater than the room. Room design conditions are 75°F and 50% RH (W_{ROOM} =65 grains per pound dry air). The winter design room temperature is 70°F. Supply air enters the UFAD plenum at 60°F, and has a humidity ratio (W_{SUPPLY}) of 54 grains of water per pound of dry air. Model TAF-R (size 8) floor diffusers are to serve the interior zone while the perimeter areas will be served by CT-481 linear bar diffusers fed by PFC fan terminals fitted with high efficiency ECM motors. Hot water will be provided to the perimeter zone at 130°F.

All of the selection calculations will be based on the CBE UFAD Cooling Load Tool previously described. As suggested by the Tool, Type 2 leakage through the floor tiles will be assumed to be 0.05 CFM/ft^2 or 84 and 42 CFM in the interior and perimeter areas, respectively.

Table 4 documents the outputs from the CLDT for the all-air system parameter inputs.

CLDT output values	Interior areas	Perimeter areas
Underfloor cooling load ratio, UCLR	1.19	1.24
Zone cooling load fraction (ZF)	0.44	0.66
Zone cooling load (Btuh/h-ft^2)	6.3	26.0
Zone airside cooling load (Btuh/h-ft^2)	6.3	26.0
Average discharge temperature, °F	63.8	67.9
Return air temperature, °F	77.7	76.0
∆T between discharge and return, °F	6.3	26.0
Total supply airflow, CFM:	703	2,483
Total supply airflow rate, CFM/ft2	0.42	2.96
Diffusers' supply airflow rate, CFM:	619	2,441
Number of diffusers used:	10	6
Individual outlet airflow rate, CFM:	62	407

Table 4: CLTD outputs for all-air example

Example 1A: All-air solution for interior space

The total sensible heat gain for the interior space is 12 Btu/h-ft^2 or 20,160 Btu/h. The CBE Cooling Load Design Tool (CLDT) approximates the interior zone UFAD cooling load as 121% of the interior space TSHG or 24,192 Btu/h. Of this, 56% is assumed to be transferred directly to the supply and return air plenums leaving the remaining 44% or 10,645 Btu/h is the interior zone cooling load.

Diffuser airflow rates will be limited to a maximum of 65 CFM due to the low (0.05 inch) plenum design pressure. A single TAF-R diffuser will be placed in each of work cubicles and two such diffusers will be placed in the traffic area between the cubicles and the perimeter zone for a total of ten (10) TAF-R outlets.

Solution to example 1A:

According to the CLDT, the average interior zone diffuser supply air temperatures will be 63.8°F and a total interior space airflow rate of 703 CFM will be required. If we assume that Type 2 leakage through the raised access floor is 0.05 CFM/ft^2, the total diffuser airflow rate will be 619 CFM, thus the individual diffuser flow rates will be 62 CFM.

To assure that occupants are not subjected to excessive drafts, a distance equal to half of the diffuser spread shown in the performance table on page S10, or in this case about 15 inches, should be maintained between the occupant and the center of the outlet.

Example 1B: All-air solution for the perimeter spaces

Six foot long CT-481 linear diffuser/plenum assemblies supplied by a single PFC fan terminal will provide cooling and heating to the four 14 x 10 perimeter offices shown in Figure 8. This zone's design sensible cooling requirement (TGHG) is 17,920 Btu/h (32 Btu/h-ft2) and its latent cooling load is 1,200 Btu/h.

The 20 x 14 perimeter conference room is served by a dedicated PFC fan terminal and has design sensible and latent cooling requirements of 8,640 Btu/h (36 Btu/h-ft^2) and 1,920 Btu/h (8 Btu/h-ft^2), respectively.

Solution to example 1B:

According to the CLDT when employed at the above inputs, the average perimeter diffuser discharge temperature will be 67.9°F and a total perimeter airflow rate of 2,483 CFM will be required for sensible cooling. Of this a negligible amount (only 42 CFM) is expected to enter the space in the form of Type 2 leakage, thus the fan terminals will be sized to deliver the full design space airflow rate. As the sensible heat gain of the conference room represents approximately 33% of this, the PFC terminal serving that zone will be sized for 820 CFM while the terminal serving the individual offices will be designed for the remaining 1,663 CFM.

According to the performance data for PFC fan terminals (with ECM motors) shown on page S53, a size 10 unit will be selected to supply the conference room while a size 16 unit will be required to provide the required sensible cooling to the individual offices. The four linear diffusers in the offices will each deliver 415 CFM while those (two) in the conference room will deliver 410 CFM each.

Assuming the temperature of the air entering the fan terminal units remains constant at 67.9°F during heating operation, the hot water coils in the fan terminals will have to supply an amount heat that is equal to the perimeter net heat loss (12 MBH or 200 Btu/h per linear foot of exposure) plus that which is required to bring its supply of plenum air up to the room air temperature.

The hot water coil performance for the PFC fan terminals presented on page S54 is based on a 115°F temperature differential between the entering air and hot water supply temperatures. As such, the performance in the tables must be multiplied by the actual temperature differential, in this case 62.4°F, divided by that (115°F) assumed in the tables. In this case that derating multiplier is equal to 0.54.

Under these conditions, the size 10 PFC terminal operating at 400 CFM with a 2 row coil (at a hot water flow rate of 1.0 GPM) can supply 10.8 MBH (20.1 x 0.54) MBH of heat to the office zone. This will satisfy the zone's 8,000 Btu/h heat loss plus compensate for the heating required for heating the plenum air up to the design room temperature.

The size 16 unit serving the conference room delivering 1,400 CFM during heating operation could utilize a 1 row coil with a hot water flow rate of 0.5 GPM to produce 8.4 MBH (15.6 x 0.54) of sensible heat which would satisfy the conference room's 4,000 Btu/h perimeter heat loss plus compensate for the 3,700 Btu/h required for heating the plenum air up to the design room temperature.

Figure 9 below illustrates the diffuser and terminal unit layouts for the all-air solutions described.

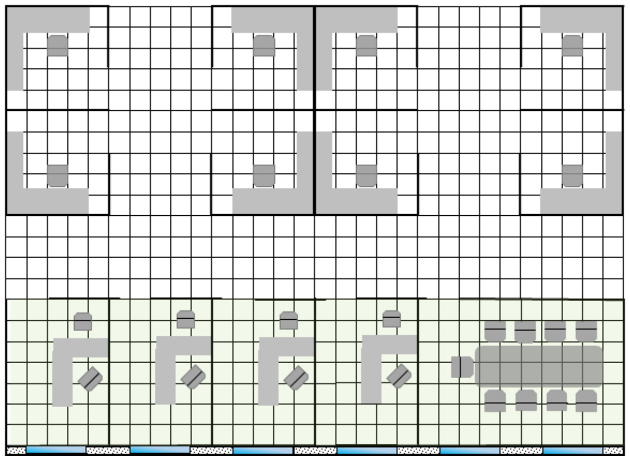


Figure 9. All-air UFAD configuration for example 1

Example 2: Air-water solution for perimeter office spaces

The perimeter zones escribed in Example 1 could also have been provided with passive chilled beams and concealed low level fin tube heating in lieu of fan terminals. In this case, all of the perimeter areas' ventilation air and space latent cooling as well as any sensible cooling that exceeds the capacity of the passive beams will be provided by floor plenum air.

Chilled water will be supplied to the beams at 58°F while the air temperature entering the beams will be assumed to be 80°F. Under these conditions, six foot long passive beams with a 20 inch width can each provide 3,300 Btu/h of sensible cooling when supplied 2 GPM of chilled water. Hot water at 130 F will be supplied to the TAF-L-W units for heating.

Solution:

Passive beams are applied directly adjacent to the perimeter glazing (as shown in Figure 6). The beams are each capable of removing 3,300 Btu/h of sensible heat or 550 Btu/h per linear foot of length. If 6 beams, each 6 feet long are employed, the perimeter area sensible cooling load borne by the plenum supply air will be reduced by the 19,800 Btu/h provided by the beams, resulting in an airside sensible cooling requirement of only 6,760 Btu/h.

The CLDT (see table 5 above) indicates that the resultant perimeter area plenum cooling load produces a higher perimeter diffuser discharge

CLDT output values	Interior areas	Perimeter areas
Underfloor cooling load ratio, UCLR	1.19	1.24
Zone cooling load fraction (ZF)	0.44	0.66
Zone cooling load (Btuh/h-ft^2)	6.3	26.0
Zone waterside cooling load (Btuh/h-ft^2)	0.0	19.4
Zone airside cooling load (Btuh/h-ft^2)	6.3	6.6
Average discharge temperature, °F	66.8	70.0
Return air temperature, °F	76.9	76.3
ΔT between discharge and return, °F	10.1	6.3
Total supply airflow, CFM:	973	812
Total supply airflow rate, CFM/ft2	0.58	0.97
Diffusers' supply airflow rate, CFM:	889	770
Number of diffusers used:	14	12
Individual outlet airflow rate, CFM:	64	64

Table 5: CLTD outputs for air-water perimeter example

temperature of 70°F despite reducing the sensible cooling airflow requirement to 812 CFM as opposed to the 2,483 CFM required by the all-air solution. However, the perimeter airflow rate is also responsible for providing all of the latent cooling so a check to make sure this airflow rate is adequate to perform that function must be made. In this case, the total latent cooling requirement for the perimeter areas was specified as 3,880 Btu/h and the humidity ratio differential (ΔW) between the room and supply air is 11 grains. The perimeter area latent airflow requirement (CFM_{LAT}) can be calculated as follows:

$$CFM_{LAT} = \text{Latent heat gain} / (0.69 \times \Delta W) = 511 \text{ CFM}$$

This is less than the 812 CFM required for sensible cooling so we can safely proceed without concern over adequate space latent cooling.

TAF-L-W performance data is shown on page ___. These terminals supply 64 CFM of plenum air when subjected to the design plenum pressure of 0.05 inches H_2O. Supplied by 4 GPM of hot water 115°F warmer than their entering air, each TAF-L-W will produce 3,383 Btu/h of heat. This

Figure 11. TAF-R diffusers in an under seat application

must be modified for the actual temperature differential (60°F) being used by applying the multiplier of 0.54 to the table's data, resulting in a unit heating capacity of 1,825 Btu/h. In order to offset the perimeter heat loss of 12 MBH, seven TAF-L-W terminals will be used, one per office and three in the perimeter conference room. This will also contribute 448 CFM toward the perimeter area's 770 CFM airside cooling requirement while the TAF-L-W coil remains off. The remaining 322 CFM will be delivered by five TAF-R diffusers, one located in each perimeter space.

The CLDT also suggests, however, that the interior area airflow requirement will increase as the reduced velocity through the plenum has increased the plenum air's residency time. In this case, the CLDT indicates that the interior area supply air temperature has increased to 66.8°F. This results in a corresponding 270 CFM increase in the interior area airflow rate. If TAF-R diffusers are to be limited to 65 CFM or less, fourteen (14) outlets will now be required to accommodate the interior area diffuser airflow increase from 619 to 889 CFM.

In summary, the air-water solution results in an overall UFAD system cooling airflow rate reduction from 3,186 to 1,785 CFM by applying the air-water solution. This also resulted in higher discharge air temperatures and reduced concern over thermal decay within the plenum itself.

Figure 10 below illustrates the layout of the air-water solution.

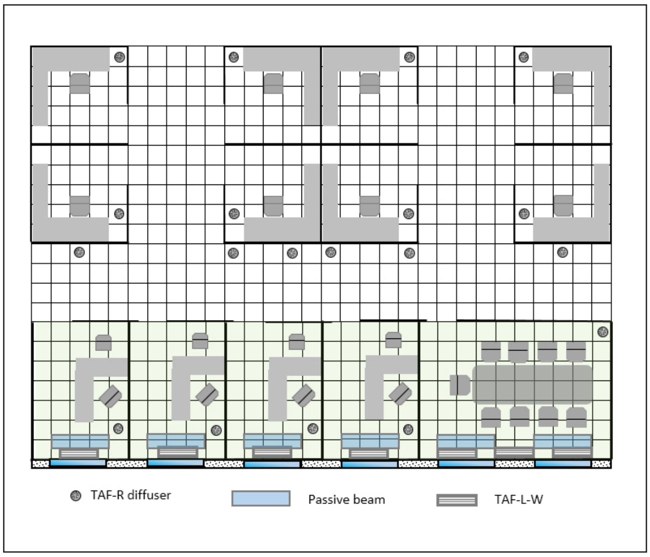


Figure 10. Air-water UFAD configuration for example 2

UNDER SEAT AIR DISTRIBUTION

Titus TAF-R swirl type diffusers are also often used to provide cooling and ventilation to theatres, performing arts centers and other public assembly applications. The diffusers are mounted directly beneath the seats (see Figure 11) and thus discharge cool air in very close proximity to the space occupants. This type of air distribution is very effective as it involves conditioning only the lower levels of the space while allowing heat gains to rise naturally and pool in the upper extremities of the space.

When designing for such applications care must be taken to maintain acceptable comfort conditions. As the outlets are located directly below seated occupants it is recommended that their supply temperature be no lower than about 65°F and that they are limited to a supply airflow rate of around 50 CFM. Performing arts facilities with very stringent acoustical constraints may require that lower airflow rates be provided.