Giving Occupants What They Want: Guidelines for Implementing Personal Environmental Control in Your Building

Fred S. Bauman, P.E.
Center for the Built Environment
University of California
Berkeley, CA 94720-1839

Presented at World Workplace 99, October 3-5, 1999, Los Angeles, CA,
and published in the Proceedings.

ABSTRACT

By giving people individual control over the environmental conditions in their workplaces, designers and facility managers can help increase worker satisfaction and productivity. Task/ambient conditioning (TAC) systems allow occupants to control temperature, air flow, and in some cases lighting and sound to meet their individual needs. This technology has recently been gaining a foothold in the U.S. It is often implemented in conjunction with underfloor air distribution, which opens up opportunities for a number of efficiencies in building design and operation. In addition to improving worker satisfaction and productivity, this combined approach has the potential to improve thermal comfort and indoor air quality, reduce energy use and life-cycle building costs, and reduce floor-to-floor height in new construction. Guidelines and recommendations are presented based on recent field and laboratory research results that encourage the intelligent design, installation and operation of TAC systems using underfloor air distribution.

INTRODUCTION

The needs of building occupants are one of the major drivers in shaping today's rapidly changing work environment. Communication, computer-, and internet-based technologies enable individual workers to have tremendous control over where, when, and how they work. Advanced and flexible interior furnishings have been developed that can be configured to support a variety of individual and team work patterns. The potential economic benefits of using these and other new building technologies to achieve greater satisfaction within the workforce are known to be very large. These benefits include increased worker productivity, employee retention, reduced operating costs (fewer occupant complaints), and increased market value of facilities.

In contrast, heating, ventilating, and air-conditioning (HVAC) technology has not kept pace with the changing workplace. HVAC approaches have changed little since variable-air volume systems were first introduced 30 years ago. For the vast majority of buildings, it is still standard practice to provide a single uniform thermal and ventilation environment within each building zone, offering little chance of satisfying the environmental needs and preferences of individual occupants (unless, of course, they happen to have a private office with a thermostat). As a result, the quality of the indoor environment (i.e., thermal comfort and indoor air quality) continues to be one of the primary concerns among workers who occupy these buildings. Several documented surveys of building occupants have pointed out the high dissatisfaction with indoor environmental conditions [e.g., 1, 2]. Most recently, the Building Owners and Managers Association (BOMA), in partnership with the Urban Land Institute (ULI), surveyed 1829 office tenants in the U.S. and Canada [3]. In the survey, office tenants were asked to rate the importance of 53 building features and amenities, and to report how satisfied they are with their current office space for those same categories. The following quotes from the report demonstrate the importance of indoor environmental quality and personal control.

> *The most important features, amenities, and services to the responding tenants are related to the comfort and quality of indoor air, the acoustics, and the quality of the building management's service.*
>
> *Tenants' ability to control the temperature in their suite is the only feature to show up on both the list of most important features (96%) and the list of items where tenants are least satisfied (65%). To make an immediate and positive impact on tenants' perception of a building, landlords and managers could focus on temperature-related functions by updating HVAC systems so that tenants can control the temperature in their suite or by helping tenants make better use of their existing system.*

Task/ambient conditioning (TAC) is an innovative approach to space conditioning in commercial buildings that addresses the occupant concerns about comfort, air quality, and control described above. TAC systems are a class of building air distribution systems that deliver conditioned air and/or control the delivery of other forms of energy for space conditioning to a relatively large number of supply air locations within the building, often in close proximity to the building occupants. Compared to conventional ceiling-based air distribution systems, TAC systems are uniquely characterized by their ability to allow individuals to have some amount of control over their local environment, without adversely affecting that of other nearby occupants. As with task/ambient lighting systems, the controls for the "task" components of these systems are partially or entirely decentralized and under the control of the occupants. Typically, the occupant can control the effective temperature of the local environment by adjusting the speed and direction, and in some cases the temperature, of the incoming air supply, much like the dashboard of a car. TAC systems have been most commonly installed in open-plan office buildings in which they provide supply air and, in some cases, radiant heating directly into workstations. A large majority of these systems have been implemented in conjunction with a raised access floor system through which underfloor air distribution is used to deliver conditioned air to the space through floor grills or as part of supply outlets on the workstation furniture and partitions.

TAC systems with underfloor air distribution have several potential advantages over traditional ceiling-based air distribution systems. Well-engineered systems can: (1) improve thermal comfort by providing individual comfort control, (2) improve ventilation efficiency and indoor air quality by delivering fresh air in the near vicinity of building occupants, (3) reduce energy use through a variety of strategies including underfloor air distribution and thermal stratification, (4) reduce life-cycle building costs by improving flexibility in providing and maintaining building services, in part through the use of a raised access floor system, (5) reduce floor-to-floor height in new construction by lowering the overall height of service plenums, and (6) improve occupant satisfaction and productivity by giving individuals greater control over their local environment. These advantages will be realized only if TAC technology is appropriately designed and applied.

The purpose of this paper is to introduce and provide a brief overview of current information on TAC systems with underfloor air distribution for the following topics: benefits and guidelines for achieving them, limitations and technology needs, recent research results that improve our understanding of these systems, and ongoing work in support of wider application. For additional information, please see the references at the end of this paper.

SYSTEM DESCRIPTION

For purposes of introducing the concept of an underfloor TAC system, it is instructive to identify how these systems differ from conventional ceiling-based air distribution systems. Figures 1 and 2 show schematic diagrams of an overhead system and an underfloor TAC system, respectively, for a cooling application in an open-plan office building. Some of the most important advantages of underfloor TAC systems over ceiling-based systems occur for cooling conditions, which are required year-round in the vast majority of interior office space in many parts of the United States.

Historically, the approach to HVAC design in commercial buildings has been to supply conditioned air through extensive duct networks to an array of diffusers spaced evenly in the ceiling. As shown in Figure 1, conditioned air is both supplied and returned at ceiling level. Often referred to as mixing-type air distribution, these systems are designed to promote complete mixing of supply air with room air, thereby maintaining the entire volume of air in the space (floor-to-ceiling) at the desired setpoint temperature and ensuring that an adequate supply of fresh outside air is delivered to the building occupants. This control strategy provides no opportunity to accommodate different thermal preferences among the building occupants.

The key features of an underfloor TAC system (Figure 2) are described briefly below.

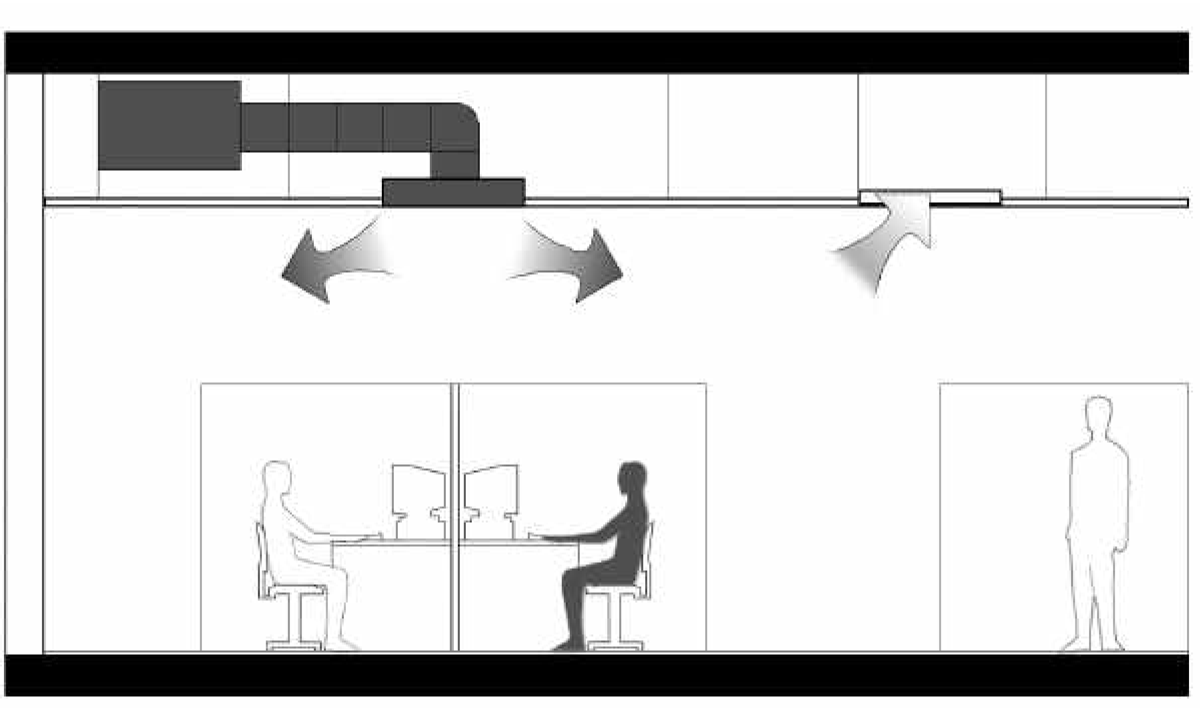

Figure 1. Conventional overhead air distribution system

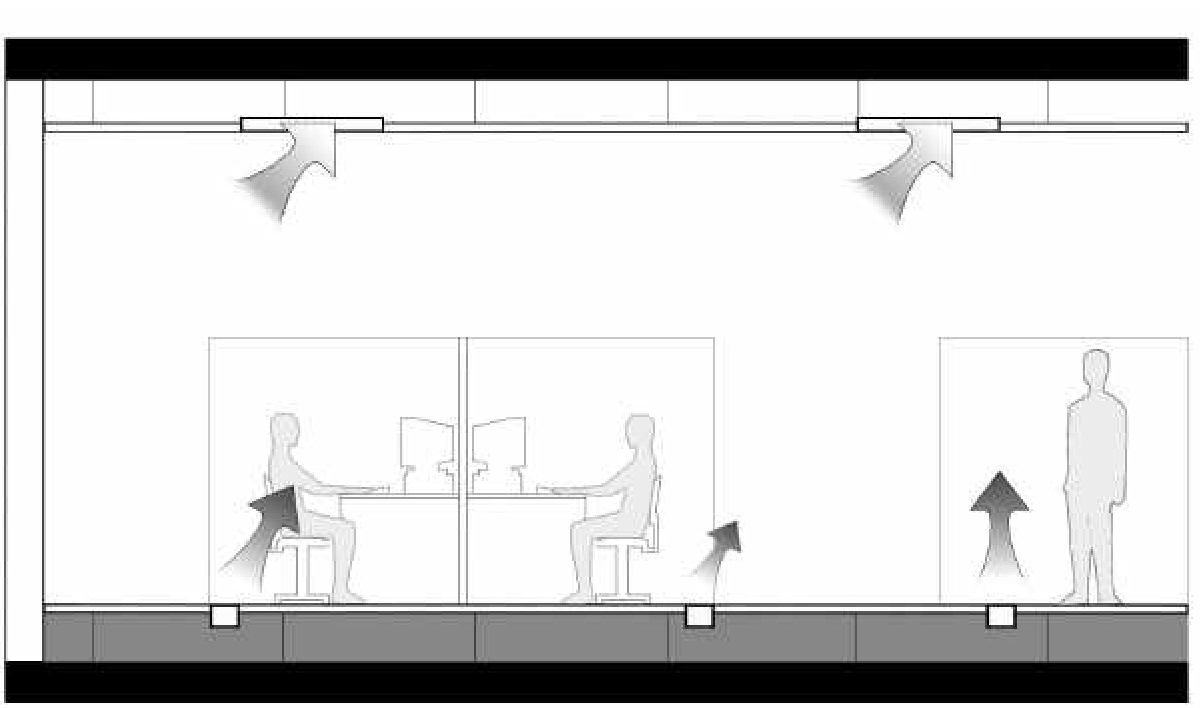

Figure 2. Task/ambient conditioning (TAC) system with underfloor air distribution

- Supply air that has been filtered and conditioned to the required temperature (cool air is predominantly needed to offset high heat load levels in interior office spaces) and humidity, and includes at least the minimum required volume of outside air, is delivered by a conventional air handling unit through a minimum amount of ductwork to the underfloor plenum. Within the underfloor plenum, the supply air flows freely to the supply outlets.
- The underfloor plenum is formed by installation of a raised access floor system, typically consisting of 2 ft x 2 ft (0.6 m x 0.6 m) concrete-filled steel floor panels. Access floors have typically been installed at heights of 12–18 in. (0.3–0.46 m) above the concrete structural slab of the building, although as will be discussed later, recent research shows that considerably lower heights are acceptable for underfloor air distribution [4]. The raised access floor system also allows all cable services, such as power and communication, to be conveniently distributed through the underfloor plenum.
- The supply air is delivered from the underfloor plenum into the occupied space through a variety of supply outlets located at floor level (shown) or as part of the workstation furniture (desktop- or partition-based). Because the air is supplied directly into the occupied zone (up to 6 ft [1.8 m] height), supply outlet temperatures are generally maintained above 63 to 64°F (17 to 18°C) to avoid uncomfortably cool conditions for the nearby occupants.
- Individual office workers can control their local thermal environment over a relatively wide range giving them the opportunity to fine-tune the thermal conditions in their workstation to their personal comfort preferences. As shown in Figures 1 and 2, a person who might feel warm with the overhead air distribution system can adjust their local floor supply unit to direct the air toward them at a higher flow rate to maintain comfort. A person feeling cool can turn down the air flow rate and direct the air away from them.
- Air is returned from the room at ceiling level producing an overall floor-to-ceiling air flow pattern that takes advantage of the natural buoyancy produced by heat sources in the office and more efficiently removes heat loads and contaminants from the space. In contrast to the well-mixed room air conditions of the conventional overhead system, stratification is actually encouraged above head height where increased temperatures and higher levels of pollutants will not affect the occupants.

Although not shown in Figure 2, there are three basic approaches to configuring the supply-air side of an underfloor TAC system: (1) pressurized underfloor plenum with a central air handler delivering air through the plenum and into the space through grills/diffusers; (2) zero-pressure plenum with air delivered to the space through local fan-driven supply outlets in combination with the central air handler; and (3) in some cases the supply air is ducted through the underfloor plenum to the supply outlets. Finally, if an underfloor plenum is not an option during a retrofit project, supply air can be ducted down from the existing overhead air distribution system to desktop- or partition-based supply outlets to provide task/ambient conditioning, although without the benefits of underfloor air distribution. Alternatively, ceiling-mounted supply outlets have been introduced for easier conversion from conventional overhead systems. These have generally resembled a large ducted adjustable jet nozzle (a large version of supply nozzles commonly found in airlines) that injects the air downward at a high enough velocity to reach the occupant's level.

TAC BENEFITS AND HOW TO ACHIEVE THEM

The potential benefits of task/ambient conditioning systems using underfloor air distribution are summarized briefly below. Recent research findings that improve our understanding as well as guidelines on how to achieve these benefits are also presented. Traditional ceiling-based supply and return air distribution systems are used as a basis for comparison in the following discussion.

Improved thermal comfort for individual occupants
Perhaps the greatest potential improvement is in occupant thermal comfort, in that individual preferences can be accommodated. In today's work environment, there can be significant variations in individual comfort preferences due to differences in clothing, activity level (metabolic rate), and individual preferences. As an example of the variations that commonly occur, a person walking continuously around in an office (1.7 met) will experience an effective temperature of the environment that is approximately 3 to 5°F (2 to 3°C) warmer than that for a person sitting quietly at their desk (1.0 met), depending on clothing level. Recent laboratory tests show that commercially available TAC supply outlets provide personal control of equivalent whole-body temperature over a sizable range: up to 16°F (9°C) for desktop TAC outlets and up to 9°F (5°C) for floor-based TAC outlets [5]. This amount of control is more than enough to allow individual thermal preferences to be accommodated.

By allowing personal control of the local thermal environment, TAC systems have the potential to satisfy all occupants, as compared to the 80% satisfaction quota targeted in practice by existing thermal comfort standards (although even this seemingly low target is not usually met in buildings) [6, 7]. As further support for providing personal control, recent field research has found that building occupants who have no individual control capabilities are twice as sensitive to changes in temperature compared to occupants who do have individual thermal control [8, 9]. What this indicates is that people who know they have control are more tolerant of temperature variations, making it easier to satisfy their comfort preferences.

Improved ventilation and indoor air quality
Some improvement in indoor air quality is expected by delivering the fresh supply air near the occupant at floor or desktop level, allowing an overall floor-to-ceiling air flow pattern to more efficiently remove contaminants from the occupied zone of the space. These benefits can be achieved in the following three ways. (1) An optimized strategy is to control supply outlets to allow mixing of supply air with room air only up to head height (6 ft [1.8 m]). Above this height, stratified and more polluted air is allowed to occur. The air that the occupant breathes will have a lower percentage of exhaust compared to conventional uniformly mixed systems. (2) Extremely high ventilation performance is achievable under certain TAC system configurations and operating strategies. In a laboratory study comparing the ventilation performance of two desktop TAC systems, significant improvements in the air change effectiveness at the occupant's breathing level (60-90% higher than well-mixed conventional systems) were measured for two desktop TAC systems supplying 100% outside air at low flow rates [10]. (3) Another benefit of providing local air supply is that it improves air motion in the space and prevents the sensation of stagnant air conditions, often associated with poor air quality.

Adaptability to non-uniform loads and improved removal of local heat sources
The above described floor-to-ceiling air flow pattern supports the efficient removal of heat loads from the space as the warm exhaust air rises up and out of the space with only partial mixing with the room air. Locally high heat loads can be easily handled with underfloor TAC systems by placing additional supply outlets (increasing supply volume) or special cooling units in the underfloor plenum near the heat sources. Alternatively, high heat loads can be directly exhausted through dedicated duct systems in the underfloor plenum. The stronger thermal plume rising above larger heat sources can also serve to naturally increase localized cooling by entraining additional cooler room air from low elevations in the space surrounding the heat sources.

Reduced building energy use
In a well-engineered underfloor TAC system designed to handle the dominant cooling loads in interior zones of office buildings, there are several energy-conserving strategies that can be implemented. Cooling energy savings can be obtained by reducing air-conditioning requirements outside of the occupied workstations and by allowing some amount of controlled thermal stratification in the space. Due to the increased air movement and cooling capability provided by the local supply diffusers, higher average space temperatures can be maintained and greater temperature variations (slow drifts) can be allowed to occur in response to the outside daily cycle. In TAC systems using fan-powered local supply

units, the energy use associated with the small fans and their electric motors can be minimized by shutting off equipment in unoccupied workstations using occupancy sensors. This reduction in energy use can be significant as by some estimates, open-plan office workstations in the United States are only occupied on average 50% of the time.

Due to extremely low operational static pressures in underfloor air supply plenums (typical pressures are 0.1 in. H_2O [25 Pa] or less), central fan energy use can potentially be reduced relative to traditional ducted overhead air distribution systems depending on the design strategy adopted [11]. For variable air volume operation, a recent technical manual estimates that central fan energy use can typically be reduced by 20-30% [12]. This estimate accounts for (1) 20% reduction in supply volume due to stratification benefits, (2) 40% increase in supply volume due to higher supply air temperature, and (3) 40% decrease in typical system static pressure. Annual building energy simulations have estimated that an office building in the San Francisco Bay area with a desktop TAC system using the above strategies can save as much as 18% of the cooling energy, 18% of the distribution (fans and pumps) energy, and 10% of the total electricity [13].

Under the right climatic conditions, higher supply air temperatures allow extended hours of operation of an outside-air economizer. Using a 24-hour thermal storage strategy in the exposed structural mass of the floor plenum, peak cooling loads (and electric utility peak demand charges) can be reduced, cooling equipment can be downsized, and nighttime precooling of the thermal mass can take advantage of extended economizer operation (under suitable outside air conditions). Reduction in the summer peak demand using thermal storage is estimated to be as high as 40% by Spoormaker [14] and 30% by Shute [15].

Lower life-cycle building costs

Costs are usually the most important consideration in choosing a building system. First costs for TAC systems utilizing raised access flooring will probably, although not necessarily, be slightly higher than those for a conventional system. However, the cost of the raised floor can be at least partially offset by savings in installation costs for ductwork and electrical services, as well as from downsizing of some mechanical equipment. If a raised access floor system has already been selected for other reasons, such as improved cable management, underfloor air distribution can be easily shown to be cost effective. In new construction, underfloor air distribution can lead to reduced floor-to-floor heights. This is accomplished by reducing the overall height of service plenums. A single large overhead plenum to accommodate large supply ducts (Figure 1) can be replaced with a smaller ceiling plenum for air return combined with a lower height underfloor plenum for unducted air flow and other building services (Figure 2). Operating costs can be reduced in accordance with the energy-saving strategies discussed above. With the improved thermal comfort and individual control provided by TAC systems, occupant complaints requiring response by facility staff can be minimized. In addition, with most of the building services now located in the underfloor plenum, labor costs for maintenance and cleaning are reduced due to working at floor level instead of on ladders or scaffolds in the overhead plenum.

Improved flexibility in providing and maintaining building services

Underfloor TAC systems using raised access flooring provide maximum flexibility and significantly lower costs associated with reconfiguring building services [16-18]. Floor-based supply outlets can be easily relocated (by simply exchanging floor panels) using in-house personnel in response to changes in people or equipment. This flexibility can be especially important over the lifetime of buildings having high churn rates.

Improved occupant satisfaction and increased worker productivity

TAC systems can potentially increase the satisfaction and productivity of occupants as a result of their having the ability to individually control their workspace environments. The financial implications of such improvements can be extremely large since salary costs typically make up at least 90% of all costs (including construction, renovation, operation, and maintenance) over the lifetime of a building. Field measurements and occupant surveys taken before and after the installation of a desktop TAC system showed significantly higher satisfaction with the temperature level and temperature control for the occupants who received a desktop TAC unit compared to a control group of those who did not receive such a unit [8]. Another well-known field study of desktop TAC units with underfloor air distribution concluded that the desktop TAC system was responsible for a 2.8% increase in worker productivity [19]. A recent analysis of previous research indicates that individual control of local cooling and heating equivalent to ±5°F (3°C) can improve group work performance by 3% to 7%, depending on the nature of the task [20]. These percentages, though small, have a life-cycle value approximating that of the entire building!

IF UNDERFLOOR TAC SYSTEMS ARE SO GREAT, WHY AREN'T THERE MORE OF THEM?

In spite of the advantages of underfloor TAC systems, there exist some barriers (both real and perceived) to widespread adoption of task/ambient conditioning technology. These are summarized below along with recent research findings and other ongoing efforts to address these technology needs.

New and unfamiliar technology

For the majority of building owners, developers, facility managers, architects, engineers, and equipment manufacturers, TAC systems still represent a relatively new and unfamiliar technology. The decision to select a TAC system will initially require changes in common practice, including new procedures and skills in the design, construction, and operation of such systems. This situation creates some amount of perceived risk to designers and building owners. A designer may incur added up-front costs associated with selling the idea of TAC technology to the client. Cost incentive programs by local power utility companies could help to compensate designers of energy-efficient TAC systems for any higher first costs during the design phase of the project.

Perceived higher costs

The perceived higher cost of TAC systems is one of the main reasons that TAC technology is not used more widely by the industry today. Many designers immediately eliminate underfloor TAC systems from consideration due to concern about higher first costs of the raised access flooring. However, as described above, there are many factors associated with TAC systems using raised access flooring that can reduce TAC life-cycle costs relative to traditional air distribution systems. In TAC systems using fan-powered supply diffusers, the additional cost of installing and maintaining these many small units must be balanced against the benefits of providing personal environmental control (reduced occupant complaints) and reducing the size of other system components (e.g., central fan).

Limited applicability to retrofit construction

The installation of TAC systems and the advantages that they offer are most easily achieved in new construction. However, the widespread use of underfloor air distribution in renovation work has been restricted by the feasibility of adding a raised floor in the large majority of buildings having limited floor-to-floor heights. Current practice calls for typical raised floor heights of 12-18 inches (0.30-0.46 m). A recent full-scale field experiment has found that low-height underfloor plenums (7 inches [0.18 m] and lower) can, in fact, provide very uniform air flow performance across a 3,200 ft^2 (300 m^2) area of a building [4]. This determination should allow underfloor air distribution technology to achieve greater market penetration in retrofit construction.

Lack of information and design guidelines

Although in recent years there have been an increased number of publications on TAC technology, including some with design methods [4, 12, 14, 15, 18, 21-24], there still does not exist a set of standardized design guidelines for use by the industry. Designers having experience with TAC systems have largely developed guidelines of their own. This situation is currently being addressed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the leading professional society among building engineers. A funded research project is now underway to develop and publish a design guide on TAC systems, making it available to the professional design and engineering community at large.

Problems with applicable standards and codes

Since underfloor TAC technology is relatively new to the building industry, its characteristics may require consideration of unfamiliar code requirements and, in fact, may be in conflict with the provisions of some existing standards and codes. ASHRAE publishes and maintains numerous building standards, including two of direct relevance to TAC systems.

ASHRAE Standard 55-1992 specifies a “comfort zone,” representing the optimal range and combinations of thermal factors (air temperature, radiant temperature, air velocity, humidity) and personal factors (clothing and activity level) with which at least 80% of the building occupants are expected to express satisfaction [6]. The rather strict air velocity limitations that were specified in earlier versions of ASHRAE Standard 55 were incompatible with the increased local air velocities that are possible with TAC systems. In 1992, Standard 55 was revised to allow higher air velocities, if the occupant has control over the local air speed, a feature of TAC systems.

ASHRAE Standard 113-1990 is the only currently available building standard for evaluating the air diffusion performance of an air distribution system [25]. As the current version is suitable only for evaluating a mixing-type conventional overhead air distribution system, ASHRAE is currently revising Standard 113 to include a new standardized test and analysis method for evaluating the unique characteristics of TAC systems.

Local building and fire codes also need to be considered in the installation of an underfloor air distribution system. In some jurisdictions the horizontal extent of the underfloor air supply plenum and the combustibility of cabling and other materials contained in the plenum are restricted by fire codes.

Limited availability of TAC products

Only a few manufacturers currently offer TAC products. The Japanese have been quite active in developing TAC technology during recent years, leading to a greater variety of advanced TAC products offered by several of the Japanese construction companies (e.g., partition-based supply outlets, remote controllers for occupant use, packaged air handling units configured to fit within a “service wall”) [26]. In the U.S., an advanced floor diffuser has recently been introduced by a major HVAC manufacturer, which should increase the awareness of underfloor TAC technology [12]. Additional products are still needed, however, to stimulate the market and address alternative promising design configurations.

Cold feet and draft discomfort

Underfloor TAC systems are perceived by some to produce a cold floor, and because of the close proximity of supply outlets to the occupants, the increased possibility of excessive draft. These conditions are primarily indicative of a poorly designed or operated underfloor system. Typical underfloor mixed air temperatures are above 63°F (17°C) and nearly all office installations are carpeted so that cold floors should not be a problem. Individually controlled supply diffusers allow occupants to adjust the local air flow to match their personal preferences and avoid undesirable drafts.

Problems with spillage and dirt entering underfloor air distribution systems

Although widely applicable, there are areas in buildings where access floors and underfloor air distribution are not appropriate. These areas are generally those in which spillage has the potential to occur, such as in bathrooms, laboratories, cafeterias, and shop areas. In TAC systems with floor diffusers, concern is sometimes expressed about the increased probability of spillage and dirt entering directly into the underfloor supply air stream, and therefore being more widely distributed throughout the occupied space. Most floor diffusers, however, have been designed with catch-basins (e.g., to hold the liquid from a typical soft drink spill). Tests have shown that floor diffusers do not blow more dirt into the space than other air distribution systems [27]. In addition, air speeds within the underfloor plenum are so low that they do not entrain any dirt or other contaminants from the plenum surfaces into the supply air.

Condensation problems and dehumidification in underfloor air distribution systems
In humid climates, outside air must be properly dehumidified before delivering supply air to the underfloor plenum where condensation may occur on cool structural slab surfaces. While humidity control of this sort is not difficult, given the large surface area of the structural slab in the underfloor plenum, it is important that it be done correctly. If a higher cooling coil temperature is used (allowing an increased chiller efficiency) to produce the warmer supply air temperatures needed in TAC systems, the cooling coil's capacity to dehumidify will be reduced. Possible solutions include the use of a separate system to dry outside air, or the use of desiccant dehumidification [18].

WHAT'S AHEAD?

With the growing awareness of the advantages of TAC systems and underfloor air distribution in the building industry, more of these installations will be completed in the coming years. As this occurs, it will be important to quantify the environmental and productivity benefits using TAC and underfloor technology. Building owners, developers, and other technology users need this kind of proof of performance cost-effectiveness (reduced life-cycle building costs) to overcome the barrier of higher first costs often associated with this and other intelligent building technologies. In addition, as building occupants and tenants understand more about comfort and indoor air quality issues, they will not only demand higher quality work environments, but will be willing to pay more for them.

Efforts are now underway in the following areas to provide more information and support to the building industry on TAC systems and underfloor air distribution.

- Design guidelines: As mentioned earlier, ASHRAE has initiated a research project to develop a design guide on task/ambient conditioning systems.

- Standards: ASHRAE Standard 113-1990 is currently being revised to include a new standardized test and analysis method for evaluating the performance of TAC and underfloor air distribution systems.

- Research: The author is involved in two ongoing research projects: (1) thermal and air flow performance of underfloor air supply plenums, and (2) field study comparing worker satisfaction, productivity, and system performance for TAC and conventional air distribution systems. Other research institutions are also doing work in this area.

As this and other information become available, the benefits of well-designed TAC and underfloor systems should become apparent and greater acceptance and application of this technology will occur.

CONCLUSIONS

Task/ambient conditioning (TAC) systems using underfloor air distribution represent an approach to space conditioning in buildings that has several advantages over traditional ceiling-based air distribution systems. These systems have the potential to: (1) improve thermal comfort by providing personal comfort control, (2) improve ventilation efficiency and indoor air quality, (3) reduce energy use, (4) reduce life-cycle building costs, (5) improve flexibility in providing and maintaining building services, (6) reduce floor-to-floor height in new construction, and (7) improve worker satisfaction and productivity. These advantages will be realized only if TAC technology is appropriately designed and applied. This paper has provided a current assessment of this growing and promising technology and has summarized guidelines that encourage the intelligent design, installation, and operation of TAC systems with underfloor air distribution.

ACKNOWLEDGMENTS

This work was sponsored by the Center for the Built Environment (CBE), an NSF/Industry/University Cooperative Research Center at the University of California, Berkeley. I would like to gratefully acknowledge our CBE Partners: California Department of General Services, California Institute for Energy Efficiency, HDR Architecture, Inc., Herman Miller, Inc., International Facility Management Association, Johnson Controls, Inc., Lucent Technologies, Inc., Ove Arup & Partners, Ltd., Tate Access Floors, Inc., U.S. Department of Energy, U.S. General Services Administration, Webcor Builders, the National Science Foundation, and the Regents of the University of California, who provided funding for this research.

I would also like to thank Charlie Huizenga, CBE Research Specialist, and Edward Arens, Professor of Architecture and CBE Director, for their valuable comments during their reviews of this paper, and Quoc Doan, CBE Student Researcher, and Kevin Powell, CBE Administrator, for producing the schematic diagrams.

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