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TASK/AMBIENT CONDITIONING SYSTEMS: ENGINEERING AND APPLICATION GUIDELINES

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INTRODUCTION

During recent years an increasing amount of attention has been paid to air distribution systems that individually condition the immediate environments of office workers within their workstations. 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 has control over the speed and direction, and in some cases the temperature, of the incoming air supply. Variously called “task/ambient conditioning,” “localized thermal distribution,” and “personalized air conditioning” systems, these 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 included a raised access floor system through which underfloor air distribution is used to deliver conditioned air to the space through floor grills, or in conjunction with the workstation furniture and partitions.

The purpose of this document is to present and discuss engineering and application guidelines and recommendations that encourage the intelligent design, installation, and operation of task/ambient conditioning (TAC) systems in commercial buildings. A well-designed TAC system should take maximum advantage of the potential improvements in thermal comfort, ventilation performance, indoor air quality, and occupant satisfaction and productivity, while minimizing energy use and costs. The development of these guidelines is based on a compilation of available information, including (1) TAC system design experience described in the literature, (2) laboratory experiments on several TAC systems, (3) field studies of TAC systems installed and operated in buildings, (4) computer simulations of whole-building energy use with and without TAC systems, (5) a survey of heating, ventilating, and air-conditioning (HVAC) engineers and manufacturers about TAC systems, and (6) the results of the Workshop on Task/Ambient Conditioning Systems in Commercial Buildings, May 4-5, 1995, held in San Francisco, California [Bauman 1995]. Since experience with TAC systems is still rather limited, the recommendations and guidelines contained in this guide represent our best estimates at this time of sound engineering judgment. As more information and experience becomes available, we expect to periodically revise and improve this document. The guide is intended for use by design engineers, architects, building owners, facility managers, equipment manufacturers and installers, utility engineers, researchers, and other users of TAC technology.

Definition and System Overview

A task/ambient conditioning (TAC) system is defined as any space conditioning system that allows thermal conditions in small, localized zones (e.g., regularly occupied work locations) to be individually controlled by building occupants, while still automatically maintaining acceptable environmental conditions in the ambient space of the building (e.g., corridors, open-use space, and other areas outside of regularly occupied work space). TAC systems are generally configured as air distribution systems that have a relatively large number of supply locations within the building, many in close proximity to the building occupants, as compared to a conventional ceiling-based air distribution system. 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. Depending on the TAC system design, ambient environmental

control may be provided by additional local supply outlets, or by a separate space conditioning system, but in either case under central or automatic control. Although not a requirement, the design of a majority of TAC systems has involved the use of underfloor air distribution in which supply air from a conventional air handling plant is delivered to the plenum under a raised access floor where it is allowed to flow freely through the plenum to the supply locations. Other configurations are possible, as will be discussed later in this guide.

As a means of introducing some of the major design and operational features of these systems, Figure 1 shows a schematic diagram of one possible TAC system configuration applied to an open plan office building. The key features are described briefly below.

- **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** (e.g., a floor-by-floor [compartmentalized] AHU, as shown in Figure 1) through a minimum amount of ductwork to the underfloor plenum.
- The **underfloor plenum** is formed by installation of a **raised access floor system**, typically consisting of 0.6 m x 0.6 m (2 ft x 2 ft) concrete-filled steel floor panels positioned 0.3 - 0.46 m (12 - 18 in.) above the concrete structural slab of the building. The raised access floor system also allows all cable services, such as power and communication, to be conveniently distributed through the underfloor plenum.
- Because the supply air in the underfloor plenum is in direct contact with the **concrete structural slab**, thermal storage strategies can be used to reduce peak cooling demand and downsize cooling equipment. Under the proper climatic conditions, nighttime ventilation of the underfloor plenum with cool outside air can precool the thermal mass, thus saving energy by replacing some of the sensible chiller load. The underfloor thermal mass also has the effect of providing a consistent cool air temperature reservoir (for cooling applications).
- For this system configuration, **variable-air-volume (VAV)** or **constant-air-volume (CAV) control** is used to maintain the underfloor plenum at very nearly a zero or slightly negative pressure with respect to the space.
- Under **individual control or thermostatic control**, the supply air is delivered from the underfloor plenum into the occupied space through a variety of **fan-powered supply outlets** located at floor level or as part of the workstation furniture. Because the air is supplied directly into the occupied zone (up to 1.8 m [6 ft] height), **supply outlet temperatures** are generally maintained above 17 to 18°C (63 to 64°F) to avoid uncomfortably cool conditions for the nearby occupants.

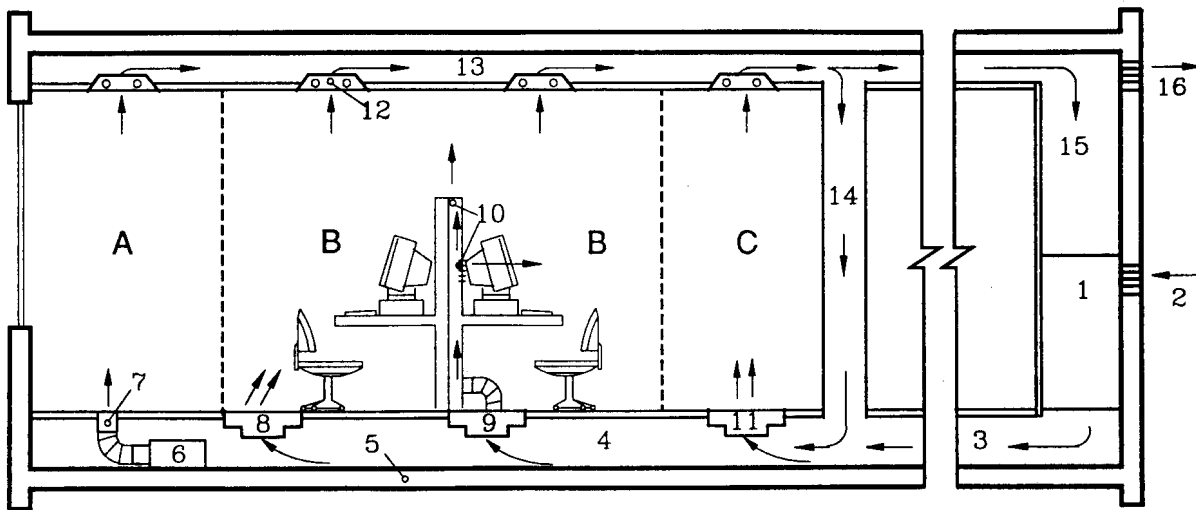


Figure 1. Schematic diagram of task/ambient conditioning system with low-pressure underfloor plenum

- | | |
|---|--|
| A. Perimeter zone | 9. Fan-powered floor unit connected to air flow partition |
| B. Interior zone with high occupancy | 10. Occupant-controlled partition-based diffusers |
| C. Interior zone with low occupancy | 11. Thermostatically controlled fan-powered floor diffuser |
| 1. Air handling unit | 12. Return air through lights |
| 2. Outside air | 13. Ceiling plenum |
| 3. Supply air to underfloor plenum | 14. Induction shaft for return air |
| 4. Underfloor plenum | 15. Return air |
| 5. Structural slab | 16. Exhaust air |
| 6. Fan-powered terminal box with reheat | |
| 7. Floor diffuser (ducted) | |
| 8. Occupant-controlled fan-powered floor diffuser | |

- Individual office workers can control their local thermal environment over a relatively wide range (typically by adjusting the volume and trajectory of the supply air entering the space), giving them the opportunity to fine-tune the thermal conditions in their workstation to their **personal comfort preferences**. Different supply outlet configurations may be used depending on the conditioning requirements for a particular zone of the building, as discussed below.
- The additional heating and cooling loads of **perimeter zones** can be handled by installing fan-powered terminal (VAV) boxes with reheat (electric or hot water) in the underfloor plenum. Under thermostatic control these VAV boxes deliver plenum air with or without reheat directly to floor diffusers through flexible ductwork to enable quick response on calls for heating (e.g., morning warm-up).

- For **interior zones with high occupancy** (e.g., workstations), two possible supply outlet configurations are shown in Figure 1. In one case, the occupant can control the direction and rate of air delivery from a fan-powered floor diffuser that is positioned near the occupant's work location. In the other arrangement, the same fan-powered floor unit can be connected to the partitions forming the workstation. Supply air passes up through the partition and can be delivered through adjustable grills at different locations above the desktop level, as shown.
- For **interior zones with low occupancy** (e.g., corridors and open-use space), thermostatically controlled fan-powered floor diffusers can be used to control conditions in this ambient space.
- Air is returned from the room at ceiling level (e.g., through recessed lighting fixtures, as shown) 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.
- Typically in this low-pressure plenum configuration, the volume of air delivered through the supply outlets to the space exceeds the primary air supply volume (negative plenum pressure) provided by the air handling unit (AHU). A certain amount of **return air** is recirculated and mixed with the primary air to produce the desired supply air temperature entering the space. Figure 1 shows that return air can be recirculated from the ceiling plenum down induction shafts (often formed with furring spaces along structural columns) directly into the underfloor plenum where it is blended with the incoming primary air from the AHU. Alternatively, return air can be taken all the way back to the AHU, where it can be more conveniently filtered and dehumidified if necessary, before mixing with the primary air and re-entering the underfloor plenum.

Figure 2 shows a schematic diagram of a second example TAC system configuration that has been more commonly applied to office buildings due to its simplicity and cost savings. Although this floor-based air distribution system provides only limited individual comfort control for occupants, it still affords many of the same flexibility and energy-saving benefits associated with the first example.

- The system configuration has many similarities with that shown in Figure 1, including a conventional AHU, either centralized or floor-by-floor (shown), that delivers primary conditioned supply air using VAV or constant-air-volume (CAV) control through a minimum amount of ductwork to the underfloor plenum where it comes in contact with the concrete structural slab.
- A major difference for this system is that the AHU maintains the underfloor plenum at a slight positive pressure, eliminating the need for most fan-assisted supply outlets. In this case, the **pressurized underfloor plenum** forces supply air through floor-level diffusers that are designed to provide rapid mixing with the room air.
- Office workers have limited control of the amount of air being delivered through the floor diffusers by adjusting a volume control damper. However, adjustments are rarely made in practice because it is not easy to do so and it is also more difficult to

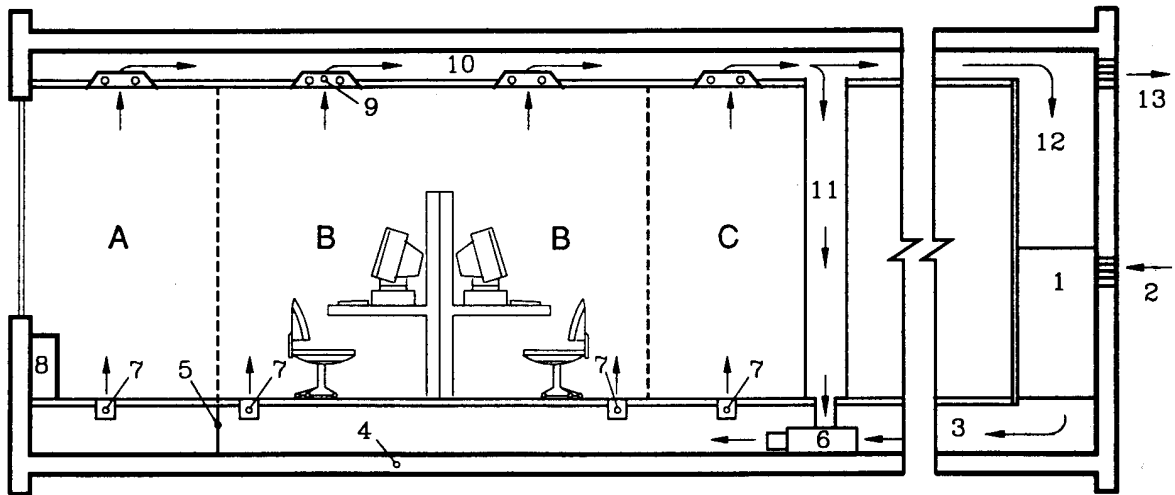


Figure 2. Schematic diagram of task/ambient conditioning system with pressurized underfloor plenum

- | | |
|--------------------------------------|---|
| A. Perimeter zone | 6. Fan-powered mixing box |
| B. Interior zone with high occupancy | 7. Floor diffuser |
| C. Interior zone with low occupancy | 8. Radiation or convection heating unit |
| 1. Air handling unit | 9. Return air through lights |
| 2. Outside air | 10. Ceiling plenum |
| 3. Supply air to underfloor plenum | 11. Induction shaft for return air |
| 4. Structural slab | 12. Return air |
| 5. Perimeter zone plenum divider | 13. Exhaust air |

determine what effect the adjustment has actually had as compared to the more positive feedback provided by the fan-assisted outlets shown in Figure 1. This type of TAC system is sometimes referred to as a **localized ventilation system**, as it provides conditioned air to the space through many localized supply outlets, but does not allow for true task conditioning, or individual control.

- **Zoning control** is handled by partitioning the underfloor plenum to correspond to the building zones having unique load requirements (e.g., the perimeter zone is shown). Separately-controlled supply air feeder ducts must deliver air to each of the partitioned underfloor zones.
- In this example, heating requirements in the **perimeter zone** are handled by an above-floor radiation or convector unit located under the window sill and served by hot water or electric heat.
- Differences in cooling requirements between **interior open plan office zones** (with high or low occupancy rates) can be controlled by using higher capacity floor diffusers, or by placing a greater number of floor diffusers in the areas with high occupancy and increased heat load density.

- This TAC system benefits from the same **floor-to-ceiling air flow pattern**, as air is returned from the room through the ceiling plenum. As discussed previously, the **return air** can be recirculated directly back into the underfloor plenum (this requires a fan-powered mixing box to blend it with the incoming primary air) or it can be recirculated back to the AHU.

Background

Historically, the approach to HVAC design in office buildings has been to supply conditioned air through extensive duct networks to an array of diffusers spaced evenly on the ceiling. A centralized control strategy has been used to control the temperature and/or volume of the air supplied from the diffusers to maintain a uniform temperature distribution in the space that also remains relatively constant over time. 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 while ensuring that an adequate supply of fresh outside air is delivered to the building occupants. In practice, building HVAC systems are operated to maintain indoor environmental conditions that are in compliance with specifications contained in national consensus building standards.

ASHRAE Standard 55-1992 [ASHRAE 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. Despite its obvious appeal, a higher percentage of satisfied occupants is not required because allowances must be made for both variations among the comfort preferences of individual occupants and individual discomfort that may arise in practice from locally-occurring nonuniform thermal conditions in the space (e.g., stratification, draft, radiant asymmetry). In addition, even when the building is maintained within the “comfort zone,” a field study of ten office buildings found that a minimum of 40% of office workers would prefer to feel either warmer or cooler [Schiller et al. 1988]. This study, along with other surveys (e.g., Croome and Rollason 1988, Harris and Associates 1989), has also indicated that stagnant air conditions are one of the most common complaints in office environments. These findings are based on occupant surveys and suggest that it is psychologically important for occupants to be able to detect some amount of air motion within their work environment.

Recent trends in today’s office environment, make it increasingly more difficult for conventional centralized HVAC systems to satisfy the environmental preferences of individual office workers using the standardized approach of providing a single uniform thermal and ventilation environment. Since its original introduction in West Germany during the 1950s, the open plan office containing modular workstation furniture and partitions is now the norm. Thermostatic control zones in open plan offices typically encompass relatively large numbers of workstations in which a diverse work population having a wide range of preferred temperatures must be accommodated. Modern office buildings are also being impacted by a large influx of heat-generating equipment (computers, printers, etc.) whose loads vary considerably from workstation to workstation. Offices are often reconfigured during the building’s lifetime to respond to changing tenant needs, affecting the distribution

of within-space loads and the ventilation pathways among and over office partitions. Compounding this problem, there has been a growing awareness of the importance of the comfort, health, and productivity of individual office workers, giving rise to an increased demand among employers and employees for a high-quality work environment.

The concept of task/ambient conditioning was developed to address many of the problems and concerns outlined above. Just as with task/ambient lighting systems, TAC systems allow ambient air-conditioning requirements to be reduced in noncritical areas. Individually controlled diffusers provide task conditioning only when and where it is needed to maintain occupant comfort. In contrast to the centralized approach described above in which a large zone of the building is controlled by a single wall thermostat, the TAC system concept approaches the optimal solution of providing a collection of many small control zones (e.g., workstations), each under the control of an ideally located and calibrated “human” thermostat. In addition, by delivering fresh air in the near vicinity of the occupants, TAC systems are more likely to provide improved air movement and preferential ventilation in the occupied zone, as compared to conventional mixing-type air distribution systems.

Underfloor air distribution, originally introduced in the 1950s in spaces having high heat loads (e.g., computer rooms, control centers, and laboratories), has proven to be the most effective method for delivering conditioned air to localized diffusers in the occupied zone of a building. In these early installations, the raised access floor system was used to handle the large amounts of cables serving the computers and other equipment. By supplying cool air through floor diffusers and returning air at the ceiling, the overall floor-to-ceiling air flow pattern supported the buoyancy-driven air movement and efficient removal of heat loads from the space. The maintenance of thermal conditions within the comfort zone was not a major focus of these early applications as they were primarily concerned with equipment cooling, not people cooling. As a result, the first floor diffusers were not designed to be easily adjustable.

In the 1970s, underfloor air distribution was introduced into office buildings in West Germany as a solution to these same cable management and heat load removal issues caused by the proliferation of electronic equipment throughout the office [David 1984, Sodec and Craig 1990]. In these buildings, the comfort of the office workers had to be considered, giving rise to the development of occupant-controlled localized supply diffusers to provide task conditioning. Some of the first TAC systems in Europe used a combination of desktop outlets for personal comfort control and floor diffusers for ambient space control [Sodec 1984, Barker et al. 1987].

Until recently, office installations using underfloor TAC systems have been found primarily in South Africa, Germany, and other parts of Europe. The technology is still not commonly used, as evidenced by its slow growth in North America, in part due to the downturn in office building construction beginning in the mid-1980s. Japan did not experience this same downturn, and as a result, significant growth in underfloor TAC technology has been observed during this period. Since 1987, more than 250,000 m² (2.7 million ft²) of office space in more than 90 buildings have been installed with underfloor TAC systems in Japan [Tanabe 1995].

Underfloor TAC systems have attracted the attention of a number of investigators who present data from test chamber studies of several floor diffusers [Barker 1985, Tuddenham 1986, Rowlinson and Croome 1987, Hanzawa and Nagasawa 1990, Arens et al. (1991, 1995), Bauman et al. (1991a, 1995), Fisk et al. 1991, Yokoyama and Inoue (1991, 1993, 1994), Fountain 1993, Fountain et al. 1994, Tanabe 1994, Faulkner et al. 1995, Matsunawa et al. 1995]. Other laboratory studies are reported in the literature describing the performance of TAC desktop supply diffusers [Arens et al. (1991, 1995), Bauman et al. 1993, Faulkner et al. 1993, Fountain 1993, Fountain et al. 1994] and partition-based supply diffusers [SHASE 1991, Zhu et al. 1995].

As more TAC system installations have been completed in recent years, the experience and knowledge-base of these systems have grown. The results of field measurements and occupant surveys have also been reported [Wyon 1988, Spoormaker 1990, Hedge et al. 1992, Kroner et al. 1992, Bauman et al. (1993, 1994), Bauman and Akimoto 1996, Matsunawa et al. 1995, Oguro et al. 1995]. Several authors have described design methods, energy performance, operating characteristics, and occupant issues for TAC systems in buildings [Tuddenham 1986, Barker et al. 1987, Genter 1989, Arnold 1990, Heinemeier et al. 1990, Sodec and Craig (1990, 1991), Spoormaker 1990, Drake et al. 1991, Imagawa and Mima 1991, SHASE 1991, Tanaka 1991, Shute (1992, 1995a), Nagoya University 1994, Houghton 1995, Matsunawa et al. 1995, McCarry 1995].

Additional references will be referred to during the discussions presented later in this guide and may also be found in the *References and Additional Reading* section.

Benefits

In this section, we present an overview of the benefits associated with TAC technology; these and other issues will be discussed in more detail later in this guide. In the design of today's modern office buildings, the selection of air-conditioning systems should be based on a broad range of issues, not just the minimization of first costs. These issues include first costs, design and installation costs, thermal comfort, air quality, energy performance, occupant satisfaction and productivity, reliability and maintenance costs, system flexibility and adaptability, and building life-cycle economics. For example, while many designers have the opinion that an underfloor TAC system has a higher first cost than that of a comparable ceiling-based HVAC system, recent economic analyses suggest that life-cycle costs for buildings using raised access floors and underfloor air distribution can be significantly lower compared to more conventional approaches [GSA 1992, York 1993, Blaevoet 1995]. Often the decision to incorporate a relatively new technology, such as a TAC system, into the design of a building is based primarily on the owner/developer's desire to use the technology in their building. However, to appeal to a larger audience in the building industry (i.e., get TAC technology into mainstream building applications), it is important that information be made available to allow a full range of system selection issues to be considered. This guide is intended to present and describe our current understanding of these issues.

The potential benefits of task/ambient conditioning systems are summarized below. Traditional ceiling-based supply and return air distribution systems are used as a basis for comparison in the discussion.

1. Improved thermal comfort for individual occupants

Occupant thermal comfort is perhaps the area of greatest potential improvement in that individual differences can be accommodated. In today's work environment, there can be significant variations in individual comfort preferences due to differences in clothing and activity level (metabolic rate). By allowing personal control of the local thermal environment, TAC systems have the potential to satisfy all occupants, including those out of thermal equilibrium with their surrounding ambient environment, as compared to the 80% satisfaction quota targeted in practice by existing thermal comfort standards [ASHRAE 1992, ISO 1984].

2. Improved air movement and ventilation effectiveness; cleaner environment

Some amount of improvement over conventional uniformly-mixed systems is expected by delivering the fresh supply air near the occupant and at floor or desktop level, allowing a floor-to-ceiling air flow pattern (with ceiling return) to more efficiently remove contaminants from the occupied zone of the space. The actual amount of this improvement still requires further research as will be discussed later.

3. Adaptability and improved removal of locally high heat loads

The above-described floor-to-ceiling air flow pattern supports the efficient removal of heat loads from the space as the buoyancy-driven 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.

4. 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 smaller volume of occupied workstations and by allowing some amount of properly 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 additional energy use associated with the small fans and their electric motors can be at least partially, if not completely, offset 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.) and by reductions in central fan energy use due to the reduced static pressure in the floor supply plenum [Bauman et al. 1994]. 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).

5. 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 amount of this increase can be minimized and in some cases completely 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. 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. Underfloor TAC systems using raised access flooring provide maximum flexibility and significantly lower costs associated with reconfiguring building services and thus reduce life-cycle costs substantially. This flexibility can be especially important over the lifetime of buildings having high churn rates. Finally, cost considerations will be different depending on whether the installation represents new or retrofit construction.

6. Improved occupant satisfaction and the potential to increase worker productivity

TAC systems have the potential to 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 as salary costs typically make up at least 90% of all costs (including construction, operation, and maintenance) over the lifetime of a building. One recent field study [Kroner et al. 1992] concluded that the installation of a desktop TAC system did have a positive impact on worker productivity, although the exact magnitude of the effects of environmental improvements on productivity requires further study.

Limitations

There exist some issues (both real and perceived) that limit the current application of task/ambient conditioning technology. These are summarized briefly below.

1. **New and unfamiliar technology**

For the majority of U.S. building owners, developers, 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. Utility incentive programs could help to compensate designers of energy-efficient TAC systems for any higher first costs during the design phase of a project.

2. **Perceived higher costs**

An industry survey found the perceived higher cost of TAC systems to be one of the two top reasons that TAC technology is not used more widely by the industry today [Bauman et al. 1992]. Many designers immediately eliminate underfloor TAC systems from consideration out of concern for higher first costs of the raised access flooring. However, as described above, there are many factors associated with raised access floor systems that contribute to reduced life-cycle costs in comparison 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).

3. **Limited applicability to retrofit construction**

The installation of TAC systems and the advantages that they offer are most easily achieved in new construction. Some of the key system features are not always suitable for retrofit applications (e.g., access floors cannot be installed in existing buildings with limited floor-to-floor heights). Due to the tremendous size of the existing building stock, retrofit construction will play a dominant role in the future for the building industry. To gain greater acceptance, interest, and market-share, TAC systems and approaches that can be more widely applied to retrofit installations are needed.

4. **Lack of information and design guidelines**

Although in recent years there have been an increased number of publications on TAC technology (see *References and Additional Reading*), 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. The intent of this guide is to address this lack of information describing TAC technology. In addition, as more installations are completed and performance data become available, the benefits of well-designed TAC systems should become apparent and greater acceptance and application of TAC technology will result.

5. **Potential for higher building energy use**

As with any space conditioning system, a poorly designed and operated TAC system has the potential to use more energy than that used by a well-designed conventional system approach. System control issues can be very important in this regard and are discussed in the section on *Controls and Operation*; the section concludes with a list of relevant topics in need of future research to improve the overall system performance of TAC systems. The section on *Energy Use* discusses the ways in which TAC systems can impact overall building energy use. For example, the energy use of TAC systems using large numbers of small local fans may increase due to the relatively poor fan motor efficiencies in these units. One of the main objectives of this document is to provide guidance for the proper implementation of TAC systems to avoid unnecessarily high energy use.

6. **Limited availability of TAC products**

Only a few manufacturers currently offer TAC products (discussed later in *TAC Equipment*). As mentioned earlier, 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”) [Tanabe 1995]. Additional products are still needed, however, to stimulate the market and address alternative promising design configurations.

7. **Lack of standardized method for performance evaluation of TAC systems**

Existing building standards, such as ASHRAE Standard 55-92 [ASHRAE 1992] for thermal comfort and ASHRAE Standard 113-90 [ASHRAE 1990] for room air diffusion, are based on the assumption of a single uniformly-mixed indoor environment. These standards are not necessarily directly applicable to TAC systems that not only provide for thermal nonuniformities, but actually may encourage them. Efforts are now underway to revise these standards in part to ensure compatibility with TAC systems.

8. **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 and operated underfloor system. Typical underfloor mixed air temperatures are above 17°C (63°F) and nearly all office installations are carpeted so that cold floors are not a problem. Individually controlled supply diffusers allow occupants to adjust the local air flow to match their personal preferences and avoid undesirable drafts.

9. **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, including 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, and in fact, contaminant levels are generally lower in underfloor TAC systems with a floor-to-ceiling air flow pattern [Matsunawa et al. 1995]. 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.

10. 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 the 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 [Houghton 1995].

Organization of Guide

The material presented in this guide is organized into the following sections:

Task/Ambient Conditioning System Design describes the basic elements of TAC systems, the tradeoffs between different approaches, system integration issues, and differences between traditional HVAC system design.

Room Air Distribution describes the benefits of the typical room air distribution provided by TAC systems.

Standards and Codes reviews the applicable building standards and codes and discusses their compatibility with TAC technology.

Task/Ambient Conditioning Equipment describes the range of TAC products that are currently available.

Controls and Operation discusses control strategies for the optimal and energy-efficient operation of TAC systems.

Energy Use summarizes the major system design and operation issues that promote the efficient energy performance of TAC systems.

Design and Construction reviews issues associated with the design and construction phases for TAC systems.

System Costs describes the key economic considerations associated with first costs, installation costs, and operation and maintenance costs of TAC systems.

Within each section a specific list of recommendations is included with a discussion of the issues.

TASK/AMBIENT CONDITIONING SYSTEM DESIGN

Recommendations

1. When possible, use an underfloor air distribution system (raised access floor) due to advantages in reduced ductwork, reduced static pressures (reduced distribution losses and lower central fan energy use), reconfigurability, and convenient distribution of building services.
2. For cooling applications, supply outlet temperatures should be maintained no lower than in the range of 17°C to 20°C (63°F to 68°F). This can be done in combination with the recirculation of a portion of the return air directly into the underfloor plenum or all the way back to the air handling unit.
3. Air should be returned at ceiling level. Depending on the ceiling configuration, this can be done using a conventional ceiling return plenum, ducted return (concealed or exposed), or high side-wall return.
4. If the return air is recirculated directly into the underfloor plenum, it is very important to ensure that the supply and return air streams are well mixed within the underfloor plenum before delivery to the space. This can usually be satisfactorily accomplished by distributing the primary air at regularly-spaced intervals throughout the plenum. Shute (1995a) recommends distribution intervals of no greater than 9 m (30 ft). The use of fan-powered local supply units will aid the mixing of primary supply air with the return air.
5. Within the underfloor plenum, utilize the thermal storage capacity of the structural mass to reduce peak cooling demand and downsize the cooling equipment, if climate conditions permit.
6. As described below, the low-pressure underfloor HVAC system [Spoormaker 1990] and the pressurized underfloor air supply system [Sodec and Craig 1991] have advantages and disadvantages in comparison to each other. Both have been quite widely and successfully installed.
7. In retrofit applications where floor-based systems are not possible, supply units must be able to accommodate connection to an existing overhead air distribution system.
8. Desktop- and partition-based systems should be well-integrated into the design of the office furnishings and compatible with an underfloor air distribution system.
9. Consider using a combination of supply outlet configurations to more closely match spatially varying conditioning requirements. To most effectively achieve task and ambient control, it is recommended to use one air distribution system, but differentiate between task and ambient supply diffusers.
10. In new construction, consider using multiple medium to small-sized (floor-by-floor) air handling units to minimize or totally eliminate ductwork and provide improved zone

control by more closely matching the AHU capacities with the requirements of separate underfloor plenum zones.

11. A variety of conventional approaches to the treatment of perimeter heating and cooling loads can be used.
12. When underfloor air heating methods are used, supply air should be ducted from the fan-powered mixing box to the supply diffuser to allow quick response on calls for heating. The occupied zone of the space is heated very efficiently when warm air is delivered at or near floor level.

Discussion

System Configuration

In configuring a TAC air distribution system, the basic choices include: (1) underfloor plenum supply at low pressure in combination with low-powered fans to bring this air into the space; (2) pressurized underfloor plenum supply; (3) ducted supply, either through an underfloor plenum or in combination with traditional overhead duct design; and (4) some combination of the above. It is highly recommended to use an underfloor supply plenum when possible, particularly in new construction. Fewer options are available for retrofit applications in which there are no opportunities for underfloor air distribution. In these cases, existing overhead air distribution systems must be modified and ducted to localized supply diffusers. Underfloor air distribution systems have been the most widely applied TAC system and we have relied upon the experience gained from these installations in the discussion presented below.

Underfloor Air Distribution

Traditional HVAC system design is based on the delivery of conditioned air directly to the space through extensive duct networks. This configuration presents several advantages to the design engineer, including the following: (1) direct connection to the supply outlets makes centralized control more convenient; (2) air flows can be more easily measured and controlled because of the relatively high pressure drops in the distribution system; (3) first costs are generally, although not always, lower than those for TAC systems, however, duct costs can be substantial; and (4) there is great familiarity with ducted systems, and a large selection of available system components.

The selection of a raised access floor system for a modern office building, despite perceived higher first costs, is often made for one or more of the following reasons: (1) improved power and communication cable management; (2) use of the sub-floor area as a supply plenum for a floor-based TAC system; (3) flexibility and reduced costs associated with reconfiguring building services including the location of air supply outlets during remodeling over the lifetime of the building; and (4) in new construction, potential for reduced floor-to-floor heights. In a well-designed new office building with an underfloor air distribution system, because of the increased space available below the floor for air supply in comparison to a conventional ducted ceiling-based system, it is possible for the overall height of service plenums (underfloor plenum for air supply and most building services plus a smaller ceiling plenum for air return, electric lighting, and fire sprinklers) to be

reduced. The reduction of floor-to-floor heights, particularly in high-rise construction, is a very strong cost incentive for building owners and developers. One noteworthy underfloor approach being developed in Japan uses a very small (100 mm [4 in.]) underfloor plenum height [Tanabe 1995], although plenum heights are more commonly in the range of 0.3 m to 0.46 m (12 in. to 18 in.).

Underfloor air distribution systems have additional advantages over conventional ducted overhead systems. Use of the space below the floor as a supply plenum eliminates the need for a significant amount of ductwork, and reduces static pressures for the central air handling unit, thus decreasing distribution losses and reducing fan energy use. Since floor supply outlets can be easily rearranged by adding, subtracting, or simply moving floor panels, the spatial distribution of supply air can be adjusted to match nonuniform and above-average cooling demands that often occur in today's office environment.

Supply Air Temperature and Volume

For cooling applications, all underfloor air distribution systems installed in interior zones of office buildings and other heavily occupied spaces are designed to maintain supply outlet temperatures no lower than in the range of 17°C to 20°C (63°F to 68°F). The required supply outlet temperatures, as with any localized system, must be in this warmer range compared to conventional overhead systems (10°C to 16°C [50°F to 60°F]) to avoid overcooling nearby occupants. Under suitable climate conditions, this greatly increases the availability of outside air economizer use and also allows higher coil temperatures to be used if desired, thereby increasing chiller efficiencies. To maintain these warmer supply air temperatures, several design approaches have been used.

1. Under constant or variable volume control, cool primary air is mixed with warm by-passed return air at the air handler to produce supply air of the proper temperature and humidity before being delivered directly into the underfloor plenum. In this configuration, a range of coil temperatures can be specified, including low temperature air systems using ice storage.
2. The air handler delivers cool primary air directly into the underfloor plenum, where it is mixed with warm return air from the space to produce the desired average plenum temperatures. In climates where humidity control is required, cooling coil temperatures are typically in the range of 10°C to 13°C (50°F to 55°F), requiring that thorough mixing of primary and return air take place in the underfloor plenum. Delivering cooler temperature air directly into the underfloor plenum is not advisable out of concern for overcooling the plenum and producing uncomfortably cool supply air temperatures near building occupants.
3. Other less efficient versions of the underfloor system utilize reheat to maintain the desired plenum supply temperatures.

For additional discussion of the methods used to mix return air with primary air, refer to the next section on *Return Air*.

Since underfloor air distribution systems allow properly controlled stratification to exist in the space, return air temperatures are significantly higher than those found in conventional system design. Depending on the space cooling load, the ceiling-level return air

temperature is typically 8°C to 10°C (15°F to 18°F) above the floor-level supply air temperature. In comparison, a ceiling-based mixing-type air distribution system would supply 13°C (55°F) air and return 24°C (75°F) air. This comparison shows that total supply air volumes for underfloor systems will average approximately 10-30% higher than conventional supply air volumes for the same cooling load. However, primary supply air volumes can be reduced in well-designed systems that condition only the minimum amount of outside air for overall cooling and ventilation purposes and rely on high rates of recirculated air driven by fan-powered supply diffusers for additional occupant cooling. In successful designs of this type in South Africa, Spoomaker (1990) claims to have been able to reduce primary air quantities for interior zones to 25% to 30% of those required for a conventional all-air design.

Due to the significantly lower pressures in underfloor plenum supply systems relative to conventional ducted systems, it can be more difficult to control the central air handler on a variable air volume (VAV) basis. These low pressures are generally below the range accurately measured by the typical velocity/pressure sensors used in ducted systems. Alternative control methods have therefore been devised and are described in *Controls and Operation*.

Return Air

Air is typically returned at ceiling level in a TAC system. For underfloor air supply and other configurations that deliver air close to floor level, this floor-to-ceiling air movement in the space can lead to benefits associated with controlled stratification and improved ventilation effectiveness in the occupied zone. Depending on the ceiling configuration, air can be returned using a conventional ceiling return plenum, ducted return (concealed or exposed), or high side-wall return. As in any type of HVAC system, a certain amount of return air from the space may be recirculated and mixed with the incoming fresh outside air to conserve energy.

A common strategy with underfloor air distribution is to recirculate a portion of the return air, or room air close to ceiling level, directly back into the underfloor plenum where it is thoroughly mixed with the cool primary air to produce the desired supply air temperature for the floor diffusers (see Figures 1 and 2). In the low-pressure plenum system, the supply volume provided by the central air handler is typically less than the total volume provided to the space through the fan-powered supply diffusers. In this arrangement the diffusers induce return air from the space to be mixed with the primary air in the plenum. Return air can be drawn down induction shafts from the ceiling return plenum, or simply through floor-level equalizing grills from the room into the underfloor plenum. The pressurized plenum system requires a more conventional ducted fan-powered mixing box to combine return and primary air before delivering it into the sub-floor plenum (see Figure 2). In any case, the proper mixing of the supply and return air is an important factor for successful operation of this underfloor system design as it avoids delivering uncomfortably cool supply air to the space. This strategy reduces costs and loss of building volume required to contain the recirculating ductwork, particularly when a central system design is used.

An alternative approach is to take all of the return air back to the air handler where the amount to be recirculated can be filtered, bypassed around the coil or conditioned (if necessary), and then mixed with the conditioned incoming outside air before delivery to the underfloor plenum. This second approach provides for optimal control of supply air conditions in terms of temperature and humidity, filtering, and mixing. It is best applied when smaller floor-by-floor air handlers are part of the design, thus reducing the length of recirculating ductwork.

As discussed later in *Room Air Distribution*, the ventilation efficiency of a TAC system using floor-to-ceiling air flow should be slightly higher than for a conventional ceiling-based mixing-type air distribution system. If minimum outside air quantities are used in combination with larger return air quantities to maintain adequate room air velocities and temperatures, savings can be realized in central fan energy use and in reduced primary duct sizes.

Thermal Storage

From an energy savings standpoint, one of the most important features of the underfloor system may be the use of the mass of the structural slab (and access floor panels) as a thermal storage medium. Due to the good thermal contact that is possible between the plenum supply air and the building structure, it is possible to implement a control strategy that utilizes a 24-hour cycle of the thermal mass to reduce energy use, peak power, and operating costs. One note of caution, however -- in humid climates, outside air must be properly dehumidified before delivering supply air to the underfloor plenum where condensation may occur on the 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.

1. During the summer, the structural mass can be subcooled during nighttime hours, and then used to offset a portion of the peak cooling loads the following day. If the local utility rate structure has incentives for load shifting, the reduced peak electrical demand will produce savings in operating costs. This can be quite significant, as Spoormaker (1990) estimates up to a 40% reduction in summer peak demand for interior zones using a thermal storage strategy. Based on observations in an existing installation, Shute (1995a) estimates that enough thermal mass participates in a daily temperature variation cycle of 3.3°C to 3.9°C (6°F to 7°F) to allow storage of approximately 30% of a typical daily cooling load. Also, by running the cooling plant for 24 hours to handle the load, equipment can be downsized.
2. When ambient nighttime temperatures are low enough, particularly during winter and swing seasons, nighttime flushing with cool outside air can subcool the thermal mass, thus reducing the amount of mechanical refrigeration needed for the following day's cooling load. This nighttime economizer operation extends the "free cooling cycle" in comparison to conventional HVAC systems designed to meet instantaneous daytime cooling loads. An example of this application has been described by Matsunawa et al. (1995). Of course, the overall usefulness of this strategy depends on the temperature and humidity characteristics of the local climate. One must be cautioned that in winter the cool thermal mass can aggravate the need for heating during the first hours of

occupancy, particularly in perimeter zones, before internal loads take effect and cooling is needed for the remainder of the day.

3. During the winter and in climates where some amount of nighttime heating is required, the heat gain stored in the mass during the day can act to preheat the supply air prior to reheating (using electric or water-based fan coil units) at the supply outlets during the following night.

Underfloor Air Distribution System Approaches

The two principal types of underfloor air distribution systems are compared below. (1) In the low-pressure underfloor HVAC system, as described by Spoormaker (1990) and Shute (1995a), primary air from the central air handling unit is delivered to the sub-floor plenum at very nearly the same pressure as the conditioned space. Air is delivered to the space primarily through floor-based fan air terminals. (2) The second approach uses a pressurized sub-floor plenum in which the central air handler forces the supply air through floor air outlets (no local fans) into the occupied space [Sodec and Craig 1991, McCarry 1995].

The low-pressure plenum system allows the majority of the sub-floor space to be open and relies on the controllable local fan air terminals to provide variations in supply conditions as needed. The fan-powered supply diffusers maintain consistent air flow into the conditioned space, even when the underfloor plenum is opened for maintenance and other purposes. Because of the increased capacity to provide local cooling as needed from fan-powered supply diffusers, some designers prefer to specify the low-pressure plenum system for applications involving higher heat loads. In these cases, the higher heat loads are commonly due to larger amounts of electrical equipment, often requiring more access holes through the floor to accommodate wiring. Uncontrolled leakage of conditioned air through access holes in the floor, to the outside, or to adjacent control zones are eliminated with this approach. As discussed later in *Standards and Codes*, some amount of partitioning may be required by local fire codes in all underfloor supply plenum designs.

The pressurized plenum system is designed to provide similar supply conditions through all floor outlets of the same size (several models are available), and thus requires partitioning of the underfloor space to accommodate building control zones with significantly different thermal loads. When the underfloor plenum is subdivided, the system is usually configured to satisfy all cooling loads with the central plant and not with local fan coil units. Although they are routinely used, plenum dividers add complexity to the underfloor configuration, cause headaches for electricians and other service personnel, and in pressurized systems pose the possibility of leakage between separate plenum control zones. Due to the relatively low pressure (≤ 25 Pa [0.10 in. H₂O]) used in the pressurized underfloor supply air plenum, however, Sodec and Craig (1991) claim that leakage into adjacent zones is small. Pressurized underfloor systems can experience problems controlling air flow through the supply outlets when sections of the access floor panels are taken up for rerouting cables, repair, or cleaning, or if distances are too great between primary air inlet locations and supply diffusers. On the other hand, pressurized systems do not need to rely on smaller local fans (except in the use of fan-powered mixing boxes)

to distribute the supply air to the conditioned space. See *Energy Use* for more discussion on fan energy issues.

The reliability of low-pressure plenum systems with fan-powered supply diffusers is improved in comparison to the central fan-driven (pressurized plenum) approach because the low-pressure system design incorporates two or three independent subsystems, as described by Spoomaker (1990) below:

1. The primary air ventilation system satisfies all minimum ventilation and humidity control requirements and a portion of the daily cooling and heating loads. The primary air system is also responsible for pre-cooling the building thermal mass in the underfloor plenum during the nighttime with outside air (if weather conditions permit) or with mechanically-cooled air.
2. Floor-based fan air terminals serve as the localized supply units under occupant control (typically one unit is located adjacent to each work location) and also provide general space cooling under automatic control. The fan terminals draw conditioned air from the underfloor plenum and deliver it to the space.
3. Water-based fan coil units (or other means as discussed in *Perimeter Systems*) are used to remove the excess heating and cooling loads that cannot be satisfied by the other subsystems. These units are most commonly positioned in the underfloor plenum of the perimeter zones of the building, and are controlled by a local space thermostat.

The above design approach has proven to be reliable because even if one of the subsystems goes down, the others can still operate to provide partial comfort control. For example, as discussed by McGregor (1995), if the chiller or central air handler goes down, some cooling effect will still be maintained by the fan-powered floor diffusers as they draw supply air over the cool floor slab and also increase local room air movement for occupant cooling.

Desktop- and Partition-Based Supply Diffusers

In desktop- and partition-based TAC systems, some amount of ductwork or passageways in and around the furniture must be used to deliver the supply air to the outlet locations, increasing the complexity of these installations. Primary air can be provided by some sort of downshaft connected to a conventional ducted ceiling-based air distribution system, making these diffusers compatible with retrofit applications. For many of the same reasons discussed above, however, connecting to an underfloor air distribution system is preferred. The widespread use of repeatable patterns of partitions and furniture in open plan offices presents an opportunity to develop TAC system designs that are well integrated into the office furnishings. Just as a floor-based TAC system is easily adaptable to different configurations, a desk- or partition-based system that can be "plugged into" specially-designed access floor panels can reduce installation costs and increase flexibility (see Figure 1). Several partition-based TAC systems have been recently developed in Japan. Some examples are described by Hisaki et al. (1991), Imagawa and Mima (1991), Tanago and Takeda (1991), Tanaka (1991), and Matsunawa et al. (1995).

The possible locations of furniture-based supply outlets with respect to the building occupants are tied closely to the layout of the office interior. In open-use areas with fewer options for furniture-based installations, it may be necessary to use floor-based (or other) supply configurations. In the same manner, an effective strategy for laying out the supply locations and outlet types throughout the space may be to consider a combination of different outlet designs. For example, while floor-based or furniture-based supply units with jet flow characteristics may be acceptable under occupant-controlled conditions, a high mixing floor (swirl) diffuser may be preferred in open areas with no opportunity for occupant control.

Task/Ambient System Integration Issues

The design of a TAC system is like that of any HVAC system in that it must satisfy peak cooling and heating demands, as well as maintain comfort across zones with spatially varying cooling and heating loads. The effectiveness of the design will depend to a large extent on how well the task and ambient environmental control functions of the building's HVAC system are integrated together. TAC system configurations can be divided into two primary types, in which the control and operation of the task and ambient space conditioning functions may vary significantly.

1. When task and ambient control functions are designed as two distinct air distribution systems, the task system is operated in conjunction with the ambient space conditioning system, being used only when the building occupants desire local conditions to be different from ambient conditions. This configuration requires that system integration issues be considered carefully. In the most basic, and probably least effective, approach, the centrally-controlled ambient space conditioning system operates in much the same manner as in a stand-alone conventional HVAC system, maintaining uniform conditions throughout the building without any adjustment in response to the operation of the task system. In this scenario, the task, or local, conditioning components will tend to be expensive and underutilized additions to the building system, because only a relatively small percentage of the occupants will have a need to modify their local environment. This situation can occur in retrofit installations in which the task system is simply added to the building, but the existing conventional overhead system is still operated in the same manner as it was before the task system was installed.

Using a more sophisticated approach, however, overall system performance will be improved by taking advantage of advanced control strategies that allow some degree of feedback between the operation of the separate task and ambient systems. For example, in a TAC system with fan-powered local supply units, information about the number of local units on or off combined with the current ambient space temperature can allow appropriate adjustments to be made, such as resetting the task or ambient system supply temperature or volume setpoints [Imagawa and Mima 1991].

2. The second type of system configuration involves the use of one air distribution system for both task and ambient control functions. In this approach, air may be delivered through the same type of local supply outlets for both personal comfort control and the removal of the major building loads. Underfloor air distribution systems with floor supply grills often fall into this category. Compared to the first option described above, costs for this configuration will be lower and overall system controls will tend to be less complex. However, if occupant use patterns produce widely intermittent operation of local supply units, temperatures and air circulation in the building may be uneven, as discussed by Tanaka (1991). Underfloor TAC systems that allow only small amounts of occupant control (see Figure 2) are able to minimize these undesirable effects and provide relatively uniform conditions, except in the immediate vicinity of the floor diffusers, which are considered to be only temporarily occupied spaces [Sodec and Craig 1991].

Probably the best approach in terms of performance is to use one air distribution system, but differentiate between task and ambient supply diffusers. When local supply diffusers contain variable speed fans, sophisticated control strategies can be accomplished, approaching those possible with two distinct task and ambient systems. In one variation of this configuration, the volume of underfloor supply air is controlled based on a room thermostat. This supply air is delivered up through and out the top of the office partitions. Office workers can divert a portion of this supply air to control their local environment, but the total volume delivered to the local space remains under the control of the thermostat, not the occupant [Argon 1994]. See *Task/Ambient Conditioning Equipment* for more specific details of these systems.

In principle, the same central or floor-by-floor HVAC system equipment can be used as in conventional air distribution systems, making the selection of this equipment routine. In new multi-story construction, the use of medium to small-sized floor-by-floor air handling units in combination with underfloor air distribution has advantages over central air handlers in terms of minimizing or almost completely eliminating major ductwork. Small AHUs also provide improved zone control capabilities and can be more easily matched in size with separate underfloor plenum zones (created by underfloor partitions) often required by local fire codes. See additional discussion in *Standards and Codes*.

Perimeter Systems

The additional heating and cooling loads of perimeter zones can be handled with conventional approaches using dedicated equipment. The treatment of perimeter loads should always be combined with an energy-efficient design of the building envelope (e.g., advanced glazing, shading, and daylighting strategies) to minimize the adverse impact of external weather conditions. A variety of perimeter systems have been used with TAC systems (for example, see Shute 1995a and McCarry 1995). Water-based fan coil units and heat pumps have several advantages. Water distribution serving these units has small space requirements and can be conveniently delivered through the underfloor plenum. Thermal distribution with water, in comparison to air distribution, saves energy because pumping water is more efficient than moving air. On the other hand, many designers and maintenance personnel are uncomfortable with the use of cooling coils with these units because it requires condensate pans and drains in the underfloor plenum. Nevertheless, these systems have been successfully installed and operated.

Approaches to perimeter cooling have been used that eliminate the need for water-based cooling under the floor by relying on the cool underfloor air reservoir under variable volume (and temperature) control. In low-pressure plenums, a fan-powered VAV box draws air from the underfloor plenum to be used in this regard (see Figure 1), and in pressurized plenums, the underfloor plenum is divided into a separate perimeter zone in which the volume and temperature of the supply air ducted from the air handler is controlled to meet the perimeter cooling loads (see Figure 2).

For perimeter heating requirements, a variety of approaches can be used, depending on design and cost considerations. Electric or water-based reheat coils can be added to fan-powered VAV boxes (see Figure 1). In this case, supply air should be ducted from the VAV box to the floor diffuser to avoid having to heat up the exposed thermal mass in the underfloor plenum and allow quick response on calls for heating. Separate above-floor heating methods can also be used, such as electric base-board heaters, radiation or convector units under the window sill (see Figure 2), or radiant ceilings. The occupied zone of the space is heated very efficiently when warm air is delivered at or near floor level, and the risk of short-circuiting between supply and return is greatly reduced.

During the winter in open plan offices, the situation often occurs in which heating is required in the perimeter zone simultaneously with cooling requirements in the interior zone of the building driven by the typical high density of heat sources. This can lead to mixing energy losses between the two zones. This subject has been studied in detail by Nakahara and Ito (1993a, 1993b), who discuss useful design and control strategies to minimize mixing energy losses.

ROOM AIR DISTRIBUTION

Recommendations

1. For cooling applications, take advantage of the benefits of the upward moving room air caused by supplying air at or near the floor level and returning it at ceiling level. This air flow pattern can lead to energy savings associated with controlled stratification and potentially improved ventilation and contaminant removal effectiveness in the occupied zone.
2. Optimize the range of allowable cooling supply air conditions from diffusers to limit their immediate impact to the occupied zone of the space (up to 1.8 m [6 ft] height). This strategy permits increased air velocities and mixing to occur within the occupied zone, if desired for comfort, but avoids a completely well-mixed space, as is typically produced by an overhead air distribution system. Allow temperatures and contaminant levels to increase above the occupied zone.
3. For air heating applications, deliver warm air at or near floor level to take advantage of the improved heating efficiency of the occupied zone and the reduced risk of short-circuiting between supply and return (a common concern with ceiling-based supply-and-return systems).

Discussion

In California and many parts of the U.S., the vast majority of interior office space requires year-round cooling. In comparison to traditional mixing-type overhead air distribution systems, underfloor systems have advantages for cooling applications for several reasons. Typically, in TAC systems cool and fresh conditioned air is delivered to the occupied zone of the space at floor or desk level and is extracted at ceiling level. This overall upward movement of air in the room takes advantage of the natural buoyancy caused by heat gain to the space and produces a more stable and efficient room air flow pattern. The upward-moving room air distribution has the following characteristics. (1) Warm air rises into the region above the occupied zone, some exiting the space with only partial mixing with the room air. This air flow pattern creates a temperature stratification in the space leading to reductions in the cooling load by as much as 15% in comparison to a conventional ceiling-based system [Shute 1992]. (2) Space contaminants tend to also migrate upwards producing higher concentrations in the warm stratified air near the ceiling. (3) The floor-to-ceiling air flow pattern adapts naturally to locally high heat loads as the stronger thermal plume rising above these larger heat sources entrains additional cooler room air from low elevations in the space surrounding the heat sources.

A major perceived disadvantage of TAC systems in comparison to traditional overhead systems is that task supply diffusers can produce local areas in the occupied zone of the building that are outside of the thermal comfort zone, as specified by comfort standards [ASHRAE 1992, ISO 1984]. On the other hand, ceiling-based air distribution systems produce this area outside of the occupied zone (i.e., near the ceiling). By allowing

individuals to adjust the local supply diffusers to satisfy their personal comfort preferences, however, TAC systems largely eliminate this perceived limitation.

Laboratory experiments with both floor-based and desktop-based TAC systems have shown that the ventilation efficiency can be improved in comparison to mixing-type air distribution at the worker's breathing level in the occupied zone when the percent outside air is high and when supply air is directed towards the work location [Fisk et al. 1991, Faulkner et al. 1993, Faulkner et al. 1995]. Similarly, Yokoyama and Inoue (1991, 1994) studied both the low-pressure and pressurized underfloor air distribution systems (with floor diffusers) in a laboratory, and found improved ventilation efficiency and contaminant removal effectiveness in comparison to that of an overhead air distribution system. Oguro et al. (1995) describe a field study in which the performance of an underfloor air-conditioning system on one floor was compared to the performance of a ceiling-based air-conditioning system on another floor of the same building. In this field study, airborne particle concentrations were significantly lower for the underfloor air conditioning system. Additional experimental data are needed to more completely evaluate the ventilation and contaminant removal effectiveness of various TAC system configurations.

For comparison with TAC system room air distribution, it is worth reviewing displacement ventilation systems, which rely on the same upward movement of air in the room and have been widely used in Nordic countries, particularly in industrial applications. In a displacement ventilation system, air is supplied at very low velocity through large-area supply devices near floor level. Improved overall air exchange efficiency and ventilation efficiency in the occupied zone have been achieved at lower air supply volumes than with conventional ceiling-based mixing-type air distribution systems. Unfortunately, when applied to office configurations with high heat load densities ($> 20\text{-}30 \text{ W/m}^2$ [$6.4\text{-}9.5 \text{ Btu/hr-ft}^2$]) and reduced ceiling heights compared to industrial buildings, displacement systems can not satisfy the cooling demand without imposing excessive thermal stratification in the space and overly cool conditions in the occupied zone. In response to these comfort limitations recent research has suggested that higher air exchange rates should be used [Sandberg and Blomqvist 1989]. Svensson (1989) has suggested that higher outlet velocities (although still relatively low) should also be used, producing greater mixing within the occupied zone and reducing the risk of comfort problems. By permitting greater mixing to occur, air exchange and ventilation efficiency rates will not be as high as those obtained with true displacement flow. However, if the mixing is confined to the occupied zone (up to heights of 1.8 m [6 ft]), some amount of improvement in the efficiency of air exchange and ventilation can still be realized.

TAC systems differ from true displacement ventilation systems primarily in the way that air is delivered to the space: (1) higher air supply volumes are used, allowing higher cooling loads to be met, (2) air is supplied at higher velocity through smaller-sized supply outlets, and (3) local air supply conditions are generally under the control of the occupants, allowing comfort conditions to be optimized. Because of the more powerful air supply flows with TAC systems, however, it is also possible to disrupt the stable upward flow pattern in the space. For example, previous laboratory experiments [Bauman et al. 1991a, Fisk et al. 1991] demonstrated that when the Tate Task Air Module (TAM) was operated at higher air supply volumes, the cool supply jets were able to reach the ceiling, thereby minimizing stratification and producing close to uniform ventilation conditions. While this

operating strategy of providing more complete mixing parallels that of conventional overhead air distribution systems, it reduces the potential improvements in energy and ventilation performance described above. A preferred operating strategy for TAC systems would limit the immediate impact of local air supply to room air conditions within the occupied zone of the space, a subject discussed by Bauman et al. (1995).

STANDARDS AND CODES

Recommendations

1. Since 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. Applicable standards and codes should be looked at carefully; revisions and exceptions that are more compatible with TAC technology may be forthcoming as additional research results are obtained.

Discussion

Listed below are brief discussions of the applicable building standards and codes that have important provisions related to the design, installation, and operation of TAC systems.

1. **ASHRAE Standard 55-1992: Thermal Environmental Conditions for Human Occupancy [ASHRAE 1992]**

Earlier versions of Standard 55 were based on the assumption of a well-mixed and uniformly conditioned environment. TAC systems, however, usually involve greater variability of thermal conditions over both space and time. The effect of providing occupant-control has not been fully taken into account, although it is well-established that occupants will tolerate greater fluctuations in environmental conditions if they have control over them. The rather strict air velocity limitations that were specified in the previous version of Standard 55 were incompatible with the increased local air velocities that are possible with TAC systems. The recently released ASHRAE Standard 55-1992 was revised to allow higher air velocities than the previous version of the standard, if the occupant has control over the local air speed. Figure 3 in Standard 55-92 was added to show the air speed required to offset increases in temperature above those allowed in the summer comfort zone. For example, Figure 3 indicates that at equal air and radiant temperatures ($t_r - t_a = 0$), a local air speed of 0.8 m/s (160 fpm) can offset a temperature rise of about 2.6°C (4.7°F) for a primarily sedentary building occupant wearing 0.5 clo.

Standard 55-92 also specifies allowable air speeds as a function of air temperature and turbulence intensity with the objective of avoiding unwanted drafts when the occupant has no direct local control. As discussed by Fountain and Arens (1993), the draft avoidance limits are solidly based on laboratory data for temperatures below 23°C (73.5°F). At warmer temperatures, however, occupants will desire additional cooling, and increased air movement (and turbulence) is an easy way of achieving such direct occupant cooling. Standard 55-92 allows these velocity limits based on turbulence intensity level to be exceeded if the occupant has control over the local air speed.

2. **ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air Quality [ASHRAE 1989]**

Standard 62-89 provides guidelines for the determination of ventilation rates that will maintain acceptable indoor air quality. Currently under revision, the new version of

Standard 62 is expected to allow some adjustment in ventilation rates based on the air change effectiveness (ACE) of the air distribution system. Mixing-type air distribution systems can at best achieve a perfectly-mixed space, defined to have an ACE of 1.0, as determined in accordance with the proposed ASHRAE Standard 129P (see below). By definition, mixing-type systems cannot provide preferential ventilation ($ACE > 1$), in which some credit could be obtained for improved air change effectiveness at the breathing level in the space.

Standard 62 sets minimum ventilation rates for office space and conference rooms at 9.4 L/s (20 cfm) per person and reception areas at 7.1 L/s (15 cfm) per person. In the design and operation of a TAC system containing a large number of occupant-controlled supply modules, some means must be provided to ensure that minimum ventilation rates are maintained, even when people choose to turn off their local air supply.

3. **ASHRAE Standard 90.1-1989: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings [ASHRAE 1989]**

ASHRAE Standard 90.1 describes requirements for the energy efficient design of new buildings intended for human occupancy. In section 9.5.2, the prescriptive criteria for zone controls states that there can be no simultaneous operation of heating and cooling systems to the same zone. Some of the unique aspects of TAC systems may be in conflict with this requirement. For example, if occupants have control of supply air temperature for heating or cooling from their local diffusers, situations may occur in which some people are requesting heating and others are requesting cooling at the same time within the same zone. In another example, with underfloor air distribution using a precooled structural slab, if there is a call for heating (i.e., in the early morning hours of the perimeter zone), this may require local reheating of the cooled underfloor supply air to satisfy the heating demand. These and other relevant situations should be carefully considered as there are exceptions to the criteria described in Standard 90.1, and perhaps subtle differences in the operation of a TAC system compared to a conventional overhead air distribution system.

4. **ASHRAE Standard 113-1990: Method of Testing for Room Air Diffusion [ASHRAE 1990]**

ASHRAE Standard 113-90 is the only currently available building standard for evaluating the air diffusion performance of an air distribution system. The current version of Standard 113, however, is based on the assumption of a single uniformly mixed indoor environment, as provided by a conventional overhead air distribution system. This assumption is not necessarily appropriate for evaluating the performance of TAC systems that deliver conditioned air directly into the occupied zone of the building through supply outlets that are in close proximity to and under the control of the building occupants. TAC systems therefore not only provide for thermal nonuniformities in the space, but may actually encourage them. Efforts are now underway to revise Standard 113 to include a new section describing a method of test that is applicable to TAC systems

5. **Proposed ASHRAE Standard 129P: Standard Method of Measuring Air Change Effectiveness [ASHRAE in press]**

The proposed ASHRAE Standard 129P is currently a working draft and is intended to provide a test method for evaluating an air distribution system's ability to provide required levels of ventilation air to the building occupants. The results of the tests may be used to determine compliance with ASHRAE Standard 62. The possibility of taking credit for the enhanced ventilation effectiveness provided at breathing level by TAC systems is now being investigated.

6. **CEC Second Generation Nonresidential Standards [California Energy Commission 1988]**

The CEC Nonresidential Standards (Title-24) defers to applicable ASHRAE standards in most cases. Title-24 does, however, address a few areas that should be taken into consideration in the operation of TAC systems. Title-24 mandates off-hour controls for central HVAC systems. Since some TAC systems are equipped with occupancy sensors, they may, in fact, improve off-hour control by shutting down more often than the overall system. Title-24 requires thermostatic zone controls with adjustable setpoints. Since TAC systems may maintain temperature differences between locally conditioned zones (workstations) and unconditioned or centrally conditioned areas of the workplace (e.g., corridors), attention should be paid to placing zone controls in representative locations. In general, Title-24 focuses on the effects of overall systems. As a result, the integration between the local and central controls should be carefully considered. The effects of individual thermal preferences on overall air quality and comfort should also be taken into account.

7. **Uniform Building Code and Local Fire Codes**

The combustibility of cabling (power, data, communication) contained in supply air plenums in underfloor air distribution systems is an important consideration. In general, applicable codes state that placing wires and cables in an air supply plenum is not a problem as long as they are contained in conduit, or are rated to be non-combustible. Local fire codes often place restrictions on the size of open supply air plenums without any smoke breaks in the form of partitions separating the plenum into smaller zones. Typically, these fire codes limit the total area (e.g., less than 280 m² [3,000 ft²]) and horizontal dimension in one direction (e.g., less than 9 m [30 ft]) of an unobstructed underfloor air supply plenum.

TASK/AMBIENT CONDITIONING EQUIPMENT

Recommendations

1. Individual supply units and outlets should be controllable by building occupants to adjust their local thermal environments to satisfy their personal comfort preferences. At a minimum, occupants should have control over a suitably wide range of supply directions and velocities. It is currently recommended that individually controllable units supply up to at least 1–1.5 m/s (200–300 fpm) at the work location.
2. Local supply air may be driven either by local fans in combination with a central air handling unit, or by a central air handler alone. Units containing fans will tend to have the best performance in response to adjustments by occupants. Efficient and quiet fan motors should be incorporated into these designs.
3. An occupancy sensor should be associated with each fan-powered occupant-controlled unit to monitor the presence of the office worker and to turn the unit off when the workstation is unoccupied. This can be an important energy saving feature as long as it does not adversely affect the environmental control of the whole space.
4. Local controls should be accessible and easy to use by the office worker. For example, controls located on the desktop are preferred over those at floor level. Inconvenient controls will not be used, defeating their main purpose. Information and training on the use of the controls should be readily available.
5. Supply outlets should be designed to perform in a manner that responds quickly and effectively to occupant control. While diffusers with high induction ratios (e.g., swirl diffusers) reduce the risk of draft discomfort, jet diffusers may be preferred in circumstances where a broader range of local control is desired. In addition, the location of the supply outlet in relation to the user may affect acceptability. More data on occupant satisfaction and use patterns with different systems are needed, and will presumably be obtained as experience with these systems grows.
6. The minimum non-zero supply velocity of floor outlets should be low enough to allow optimization of the system performance. Previous laboratory tests under cooling conditions have shown that for typical office loads, low to medium air flow rates can be used to provide acceptable thermal comfort and potentially improved ventilation efficiency in the occupied zone, while allowing some amount of stratification to produce a warmer upper zone, thus reducing space cooling energy use in comparison to a “mixing” type ventilation system [Bauman et al. 1995]. These reduced air flow rates are lower than are currently available in some floor supply outlet designs. Lower supply velocities can also lead to: (1) reduced draft risk, (2) more of a displacement flow, producing increased stratification in the space and improved ventilation in the occupied zone, and (3) reduced noise levels.
7. It is recommended that supply units be compatible with an underfloor air distribution system. The advantages of this configuration have been discussed previously.

8. Despite the fact that they are often located close to the occupants, supply units must be able to maintain acceptable noise levels (equal or better noise control compared to those provided by conventional diffusers) at the work locations. In underfloor systems, floor supply outlets must control the entry of dirt and particulates into the air distribution system.
9. To increase flexibility and reduce installation costs, supply units should be integrated into the interior office design and be easily moved and maintained. Just as floor-based supply modules are incorporated into the access floor system, well-integrated desktop- and partition-based systems could be quite valuable in an open-plan office using large quantities of the same partitions and desk configurations. Well-integrated designs will reduce costs associated with adapting to the changing requirements of existing or new tenants over the lifetime of the building.
10. The potential advantages of providing environmental control features beyond the basic air supply direction and velocity (e.g., variable temperature, radiant heating, etc.) must be evaluated in relation to the added complexity, cost, and energy use of such a system. Additional performance data are needed to resolve this issue.

Local Supply Units and Outlets

Currently, TAC supply outlet configurations can be categorized into four primary types: floor-, desktop-, partition-, and ceiling-based. For each of these categories, some of the currently available supply units and outlets from the leading manufacturers of TAC equipment are briefly described below. Product listings are provided for information only and do not constitute a recommendation or endorsement.

Floor-Based Systems

Floor-based systems have been the most commonly installed types of TAC systems. The outlets are designed to be incorporated into a raised access floor system. Air is either drawn from a low-pressure underfloor plenum by local variable or constant-speed fans, or forced through a pressurized underfloor plenum by the central air handler, and delivered to the space through floor-level supply outlets. Floor-based TAC systems have been previously developed and used in South Africa and Europe [Spoormaker 1990, Sodec and Craig 1991], and more recently in Japan [AIJ 1993, Nagoya University 1994, Matsunawa et al. 1995] and in North America [Shute 1992, Shute 1995a, McCarry 1995].

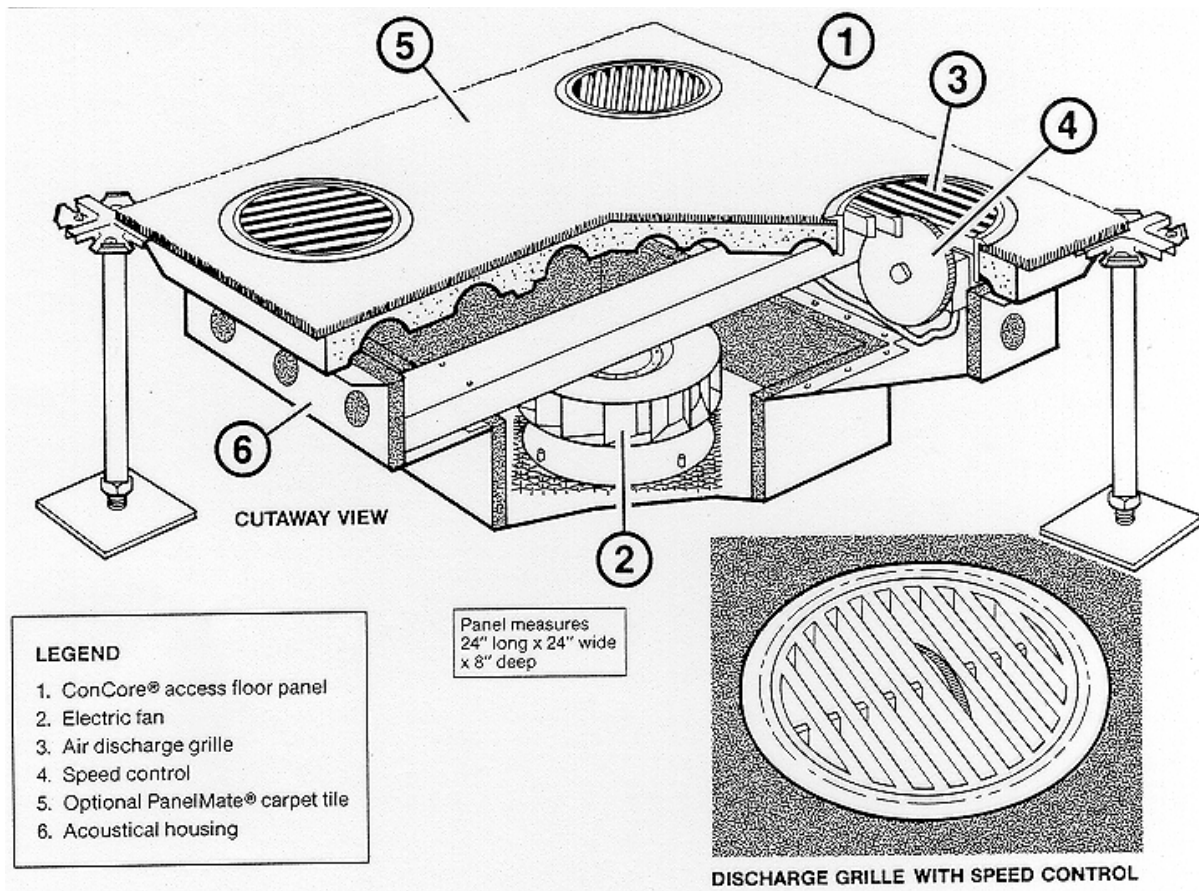


Figure 3. Task Air™ Module (courtesy of Tate Access Floors)

- Task Air™ Module (TAM) (Figure 3); available from Tate Access Floors, Inc., 7510 Montevideo Road, Jessup, MD 20794; telephone: 410-799-4200.

Floor-based supply outlets can be positioned anywhere in the building as part of a raised access floor system. Each TAM, measuring 0.6 m by 0.6 m (2 ft by 2 ft), can be located at any position simply by exchanging it with a solid floor panel of equal size. Figure 3 shows a cutaway diagram of the TAM. A fan/motor assembly draws air from the subfloor plenum and supplies it to the room through four 127-mm (5-in.) diameter discharge grilles. The grilles are molded of durable, fire-resistant polycarbonate. Individual vanes are inclined at 40° from vertical. A rotary speed control knob is recessed into one grille and each grille can be rotated 360°, allowing office workers to control both the direction and quantity of air supplied from the module.

When the fan is switched on, the TAM can deliver between 40 and 90 L/s (90 and 190 cfm) from a zero or very low pressure plenum. Because of the local fan control and jet air discharge pattern, occupants can control their local thermal conditions over a wider range than the Krantz system using swirl diffusers. However, if not properly controlled, draft discomfort can be more frequent. Results of performance testing are described by Bauman et al. (1991a, 1995). Whole-building energy simulations are presented by Bauman et al. (1994).

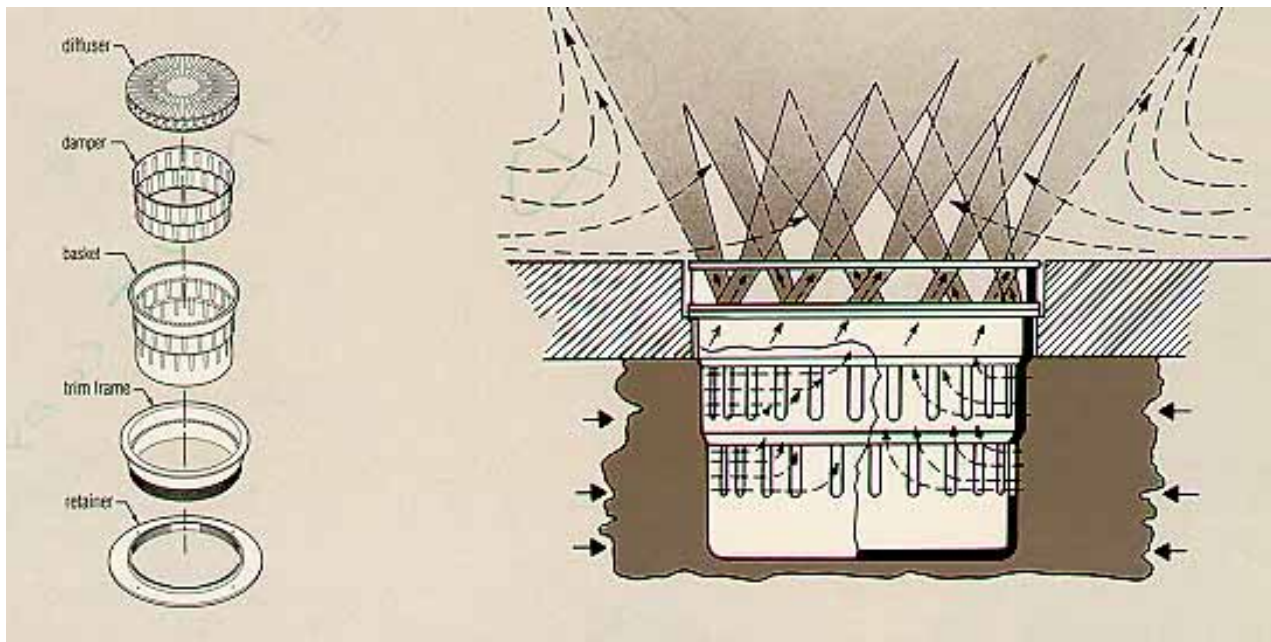


Figure 4. KB-200 floor diffuser (courtesy of Krantz)

- KB-200-ORH, KB-200 and KB-150 floor diffusers (Figure 4); manufactured by H. Krantz GmbH & Co., Aachen, Germany; available from Euro-Tech Products, Inc., P.O. Box 905, Monroe, NC 28111-0905; telephone: 704-483-2050

Floor-based supply outlets can be positioned anywhere in the building as part of a raised access floor system. The 200-mm (8-in.) diameter KB-200 and the 150-mm (6-in.) diameter KB-150 air outlets can be installed in any standard access floor panel. The Krantz outlets require a pressurized underfloor plenum. In this way, air is forced through the floor-level diffusers that are specially designed “twist” air outlets, providing rapid mixing of supply air with the room air in the occupied zone. The rated maximum volume flow rate at 17 Pa (0.07 in. wg) is 40 L/s (90 cfm) for the KB-200, and 12.5 L/s (26.5 cfm) for the KB-150. Occupants working close to the supply outlets have limited control of the amount of air being delivered by adjusting a throttle ring (volume control damper). Because supply air is driven by a central air handler (sometimes in combination with fan-powered mixing boxes), this pressurized system does not have the added complexity of operating and maintaining the many local fans that are used in the low-pressure system described above. A design guide is available [Sodec and Craig 1991].

Unlike TAC systems involving local fan control, which allow larger variations in local thermal conditions, the Krantz underfloor system is designed to maintain relatively uniform and draft-free conditions within the occupied zone. This centralized control strategy, similar to that of conventional overhead air distribution systems, imposes similar environmental conditions on all building occupants, regardless of their personal preferences. The Krantz system, however, does benefit from the many other advantages of underfloor air distribution systems.

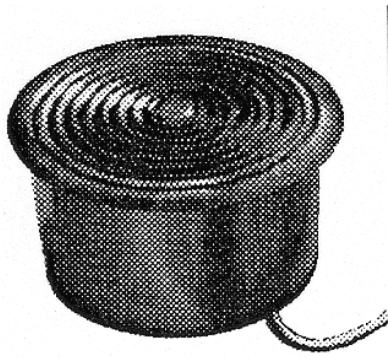


Figure 5. Milpot® (courtesy of Interface Architectural Resources)

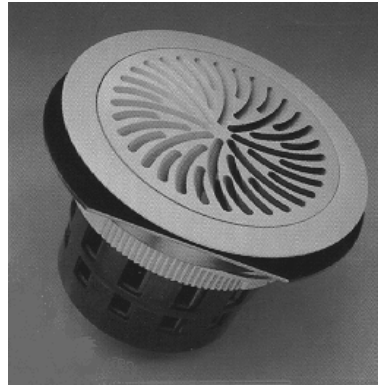


Figure 6. TAF-R diffuser (courtesy of Titus)

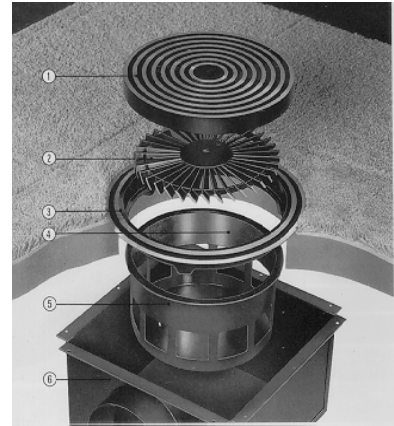


Figure 7. Type FB floor diffuser (courtesy of Trox USA)

- Milpot® and Aerlo®; available from Interface Architectural Resources, 100 Chastain Center Blvd., Suite 165, Kennesaw, GA 30144; telephone: 770-423-1723.

The Milpot® (Figure 5) is a fan-powered floor air terminal unit that can deliver air from an underfloor plenum at a user-selectable rate continuous from 7 L/s (15 cfm) to 57 L/s (120 cfm). A single Milpot® may be manually controlled by a building occupant, or a group of from one to ten Milpot® units may be automatically controlled by a remote thermostat. The Aerlo® is also a fan-powered floor air terminal unit having similar features as the Milpot®, except that the supply volume can be controlled over the range of 7 L/s (15 cfm) to 115 L/s (240 cfm).

- TAF-R diffuser (Figure 6); available from Titus, 990 Security Row, Richardson, TX 75081; telephone: 214-699-1030.

This recently released floor diffuser requires a pressurized underfloor plenum to deliver air into the occupied space with a high induction helical air pattern. The TAF-R can supply 47 L/s (100 cfm) at 20 Pa (0.08 in. wg).

- Type FB floor diffuser (Figure 7); available from Trox USA, Inc., 1005 Alderman Drive, Suite 103, Alpharetta, GA 30202; telephone: 770-569-1433.

Trox floor diffusers require a pressurized underfloor plenum, or, as shown in the manufacturer's literature, ducted air supply through the underfloor plenum. The largest Trox diffuser (FBA 200) can supply up to 60 L/s (125 cfm) at 50 Pa (0.2 in. wg).

Several other floor supply outlet designs are available, most notably in Japan and England. One recently described fan-powered floor outlet allows (1) the occupant to set the fan speed with a remote infrared controller, and (2) an adjustable air flow pattern in which supply air is delivered upward for cooling applications and horizontally along the floor for heating applications [Matsunawa et al. 1995].

Desktop-Based Systems

A variety of desktop supply outlets have been used and are available, including desktop level grills at the back of the desk surface [Barker et al. 1987, Argon 1994], free-standing directable supply nozzles at the back of the work surface [Sodec 1984, Arens et al. 1991, Bauman et al. 1993], and a linear grill at the desk's front edge directly facing the seated occupant [Argon 1994, Wyon 1995]. In all systems, conditioned air must be delivered to the supply outlet through ducts that are adjacent to the desk or incorporated into the desk design.

- Personal Environmental Module (PEM) (Figure 8), available from Johnson Controls, Inc., 507 E. Michigan Street, Milwaukee, WI 53202; telephone: 414-274-4000.

This desktop-based system has attracted a good deal of interest and research attention. In this system, each unit uses a self-powered mixing box that is hung in the back or corner of the knee space of the desk and connected by flexible duct to two supply nozzles on top of the desk. The nozzles provide free jet air flow characteristics. The mixing box uses a small variable-speed fan to pull supply air from either a slightly pressurized underfloor plenum or from flexible ducts in the office partitions supplied from the ceiling. The PEM operates ideally at a supply static pressure of 12-25 Pa (0.05-0.1 in. H₂O). At these pressures the PEM can supply a total of 6-70 L/s (12-150 cfm) through its two nozzles. Recirculated air is also drawn from the knee space through a mechanical prefilter. Both primary supply air and recirculated room air are drawn through an electrostatic air filter. The PEM has a desktop control

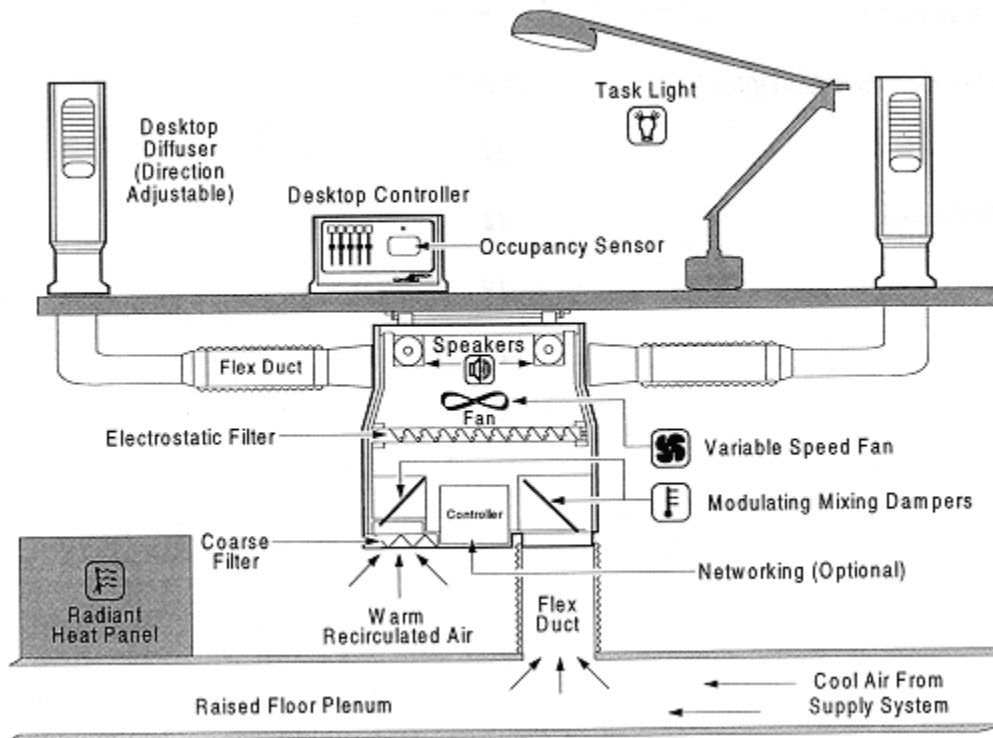


Figure 8. Personal Environmental Module (courtesy of Johnson Controls)

panel containing adjustable sliders that allow the occupant to control the speed of the air emerging from the nozzles, its temperature, the temperature of a 200-Watt radiant heating panel located in the knee space, the dimming of the occupant's task light, and a white noise generator for acoustical masking. The control panel also contains an infrared occupancy sensor that shuts the PEM off when the workstation has been unoccupied for a few minutes. The results of laboratory and field measurements are described by Arens et al. (1991), Bauman et al. (1993), Bauman and McClintock (1993), and Bauman and Akimoto (1996). Whole-building energy simulations are presented by Bauman et al. (1994).

- Desk Air Terminal (DAT); available from Argon Corporation, 5020 Tamiami Trail North, Suite 200, Naples, FL 33940; telephone: 941-643-7766.

Argon describes several different supply outlet configurations. The DAT draws supply air from an underfloor plenum through a fan-powered access floor panel. A constant volume (70 L/s [150 cfm]) of air (under the control of a room thermostat) is delivered through grills out the back of the DAT (away from the occupant) to handle ambient space loads. Using damper control, the occupant can divert a portion of the supply air out through adjustable grills towards the front of the desk to satisfy their personal comfort preferences.

- Habistat®; available from Interface Architectural Resources, 100 Chastain Center Blvd., Suite 165, Kennesaw, GA 30144; telephone: 770-423-1723.

The Habistat® diffuser is a desk-mounted supply nozzle, similar in size to the Johnson Controls PEM. In combination with a fan unit mounted under the desk, it provides up to 28 L/s (60 cfm) of heating or cooling supply air above the desktop and 2 L/s (5 cfm) below the desktop. Optional models also contain a task light, electrostatic filter, and direct connection to the underfloor supply air plenum (through an Aerlo® unit).

- Climadesk (Figure 9); available from Mikroklimat Sweden AB, Ranovagen 35, S-161 51 Bromma, Sweden; telephone: 46-8-26-60-16.

The Climadesk consists of a panel attached to the underside of a conventional desk, and connected by a flexible duct to a portable filter unit placed next to the desk. Airflow from two adjustable outlets at the front edge of the desk are used to condition the occupant's local work space. One of the supply outlets delivers supply air directly upward into the occupant's breathing zone. The other delivers air toward the occupant's body for cooling purposes. The maximum airflow from the Climadesk is only 7 L/s (15 cfm) because the air is concentrated directly on the occupant. Heating of the lower part of the body can be provided by a controllable radiant heating panel under the desk. Manikin experiments found that the temperature experienced by the occupant can be controlled using Climadesk over the range from 4°C (7°F) below to 2°C (3.5°F) above room temperature [Wyon 1995].

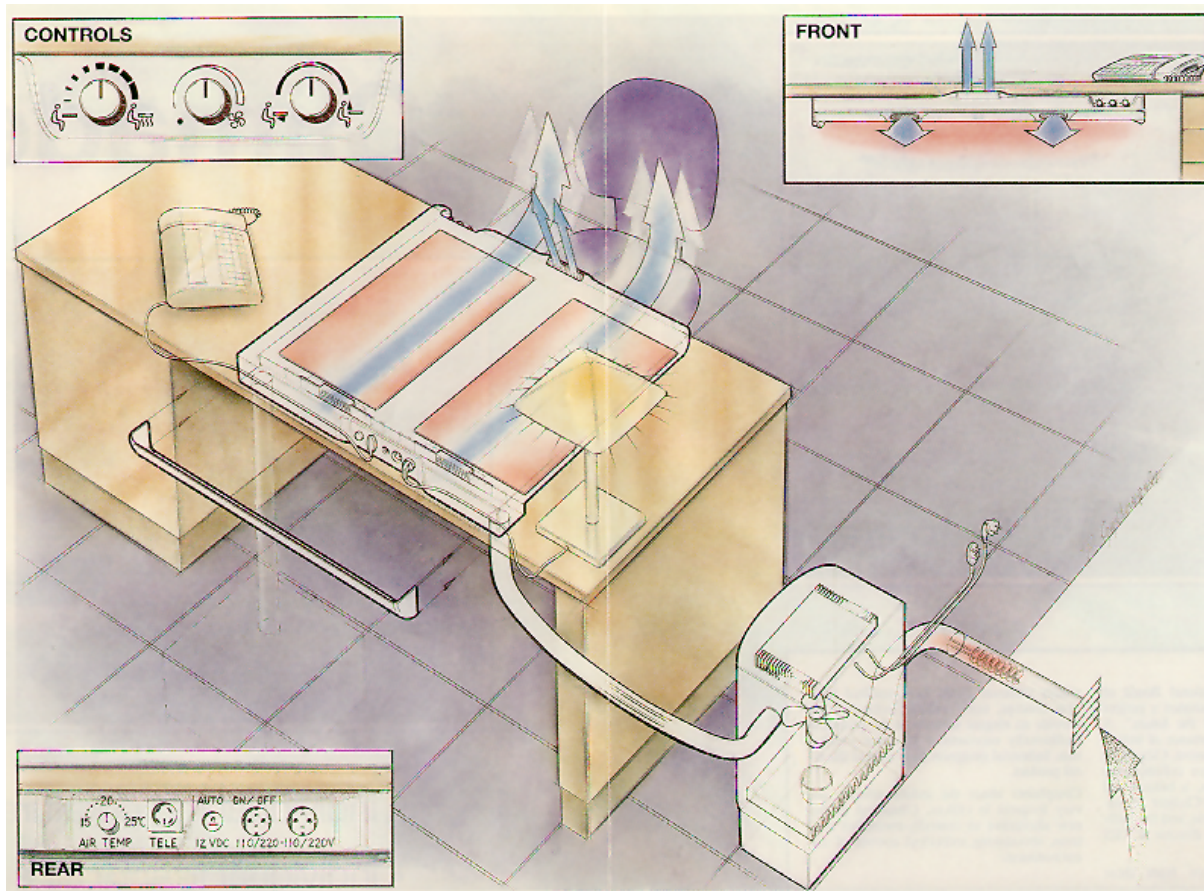


Figure 9. Climadesk (courtesy of Mikroklimat Sweden AB)

Partition-Based Systems

In recent years, partition-based TAC systems have been introduced for applications in open-plan office buildings where partitioned workstations are commonly employed. In these systems, air is delivered through passageways that are integrated into the partition design to controllable supply grills that may be located just above desk level or just below the top of the panel (for personal comfort control), or to outlets on top of the partitions (for ambient environmental control). Several of these systems installed in Japanese buildings are described by SHASE (1991). Partition- and desk-based systems are most conveniently combined with underfloor air distribution, but it is possible to feed primary air from a ducted ceiling-based system down vertical columns to the partitions and furniture.

Matsunawa et al. (1995) describe an installation in which a combination of floor supply outlets and partition-based outlets are used with an underfloor air distribution system. In this system configuration, (1) advanced floor outlets may be used (Figure 10a), (2) partitions can be used to exhaust local heat loads (e.g., larger computers) by drawing the warm air into the partition below the desk and discharging it out through openings on top of the partition (Figure 10b), and (3) partitions may be “plugged in” to floor outlet locations, providing supply air to the occupant from grills above the desk height (Figure 10c).

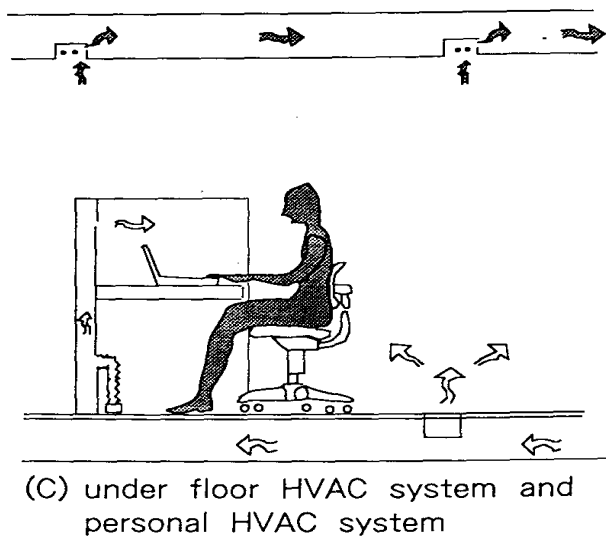
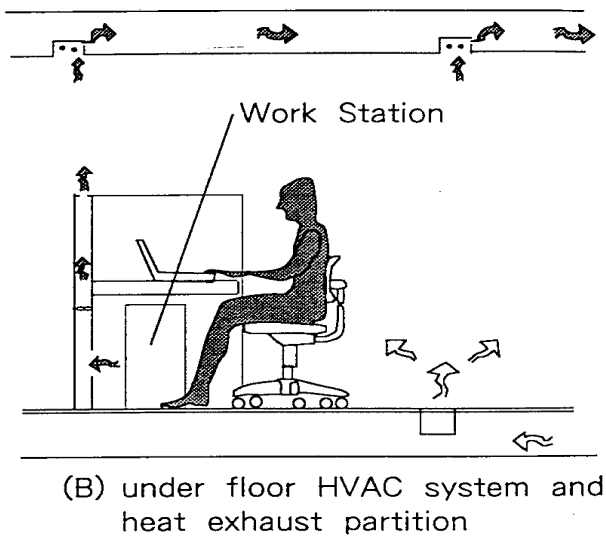
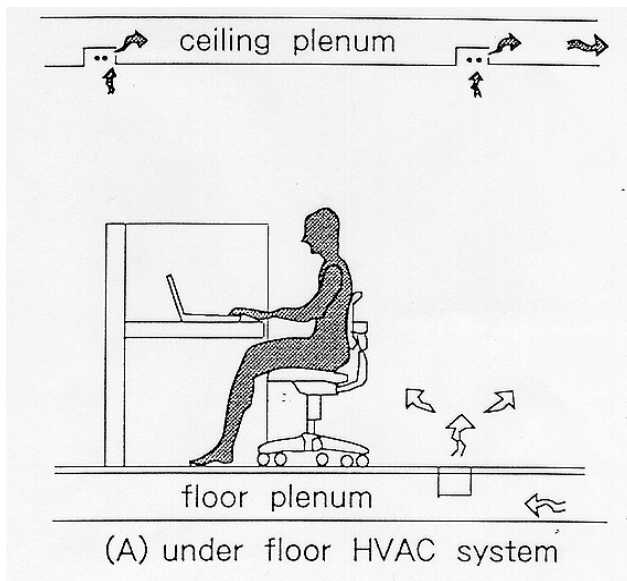


Figure 10. Underfloor air distribution system with (A) advanced floor outlets, (B) heat exhaust partition, and (C) partition-based personal HVAC system [Matsunawa et al. 1995].

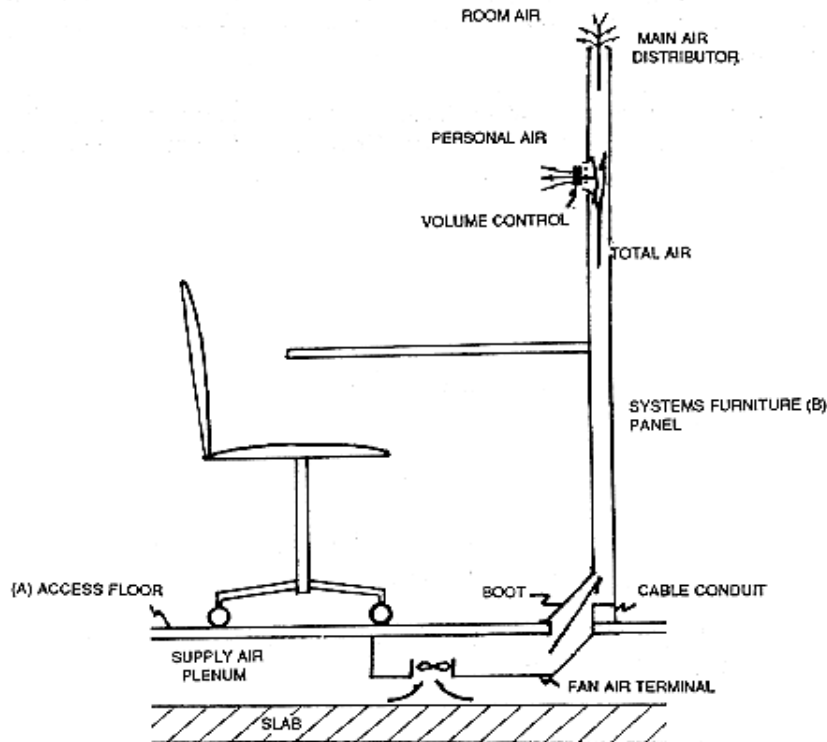


Figure 11. Panel Air Terminal (courtesy of Argon Corporation)

- Panel Air Terminal (PAT) (see Figure 11); available from Argon Corporation, 5020 Tamiami Trail North, Suite 200, Naples, FL 33940; telephone: 941-643-7766. In this recently introduced partition-based system, the volume of underfloor supply air is controlled based on a room thermostat. Air is supplied from the underfloor plenum through a fan-powered floor panel with a boot connection to the air flow partition. This supply air passes up through and out the top of the partitions to ensure that the total building loads are met. Office workers can divert (using a damper) a portion of this supply air out grills in the partitions to control their local environment, but the total volume delivered to the space remains under the control of the thermostat. An alternative approach is to use a constant volume, variable temperature control strategy based on thermostatic control (space or return temperature), thus ensuring that minimum outdoor air ventilation requirements are met [Argon 1994].

For information on other partition-based systems, see section on *Japanese Manufacturers of TAC Equipment*.

Ceiling-Based Systems

Largely in response to the needs of TAC retrofit applications to conventional ceiling-based air distribution systems, several ceiling-mounted supply outlets have been introduced. 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. In comparison to other TAC system designs, ceiling-based outlets are easier to install during renovation of spaces without raised access floors and with limited floor-to-floor height. However, due to the distance between

the supply outlet and building occupant, personal comfort control with ceiling-based systems is not as effective as with other TAC systems. A remote controller is essential for this type of system to be practical. Even so, these systems have been well-received by building occupants in some case studies reported in the literature [Tamblyn 1995]. Ceiling-based systems do not achieve the same benefits from the use of underfloor air distribution and the overall floor-to-ceiling air flow pattern found in many other TAC systems.

- Zero Complaint System (Figure 12); available from Tamblyn Consulting Services, 2 Sheppard Avenue E., Suite 200, North York, Ontario M2N 5Y7; telephone: 416-226-6565.

Large nozzles installed above each workstation are connected to the building's ceiling-based air distribution system through an automatic control damper. Cool supply air is injected downward into the workstation below each nozzle. Using an infrared remote controller, the occupant can control the amount of supply air delivered (up to 80 L/s [170 cfm]), activate an LED readout at ceiling level that shows the actual temperature, and adjust the maximum and minimum control damper openings to calibrate the thermostat with the actual workstation temperature. No local fans are involved. The direction of the nozzle can be adjusted over an angle of 15° from vertical, but this must be done manually, making it inconvenient for frequent change.

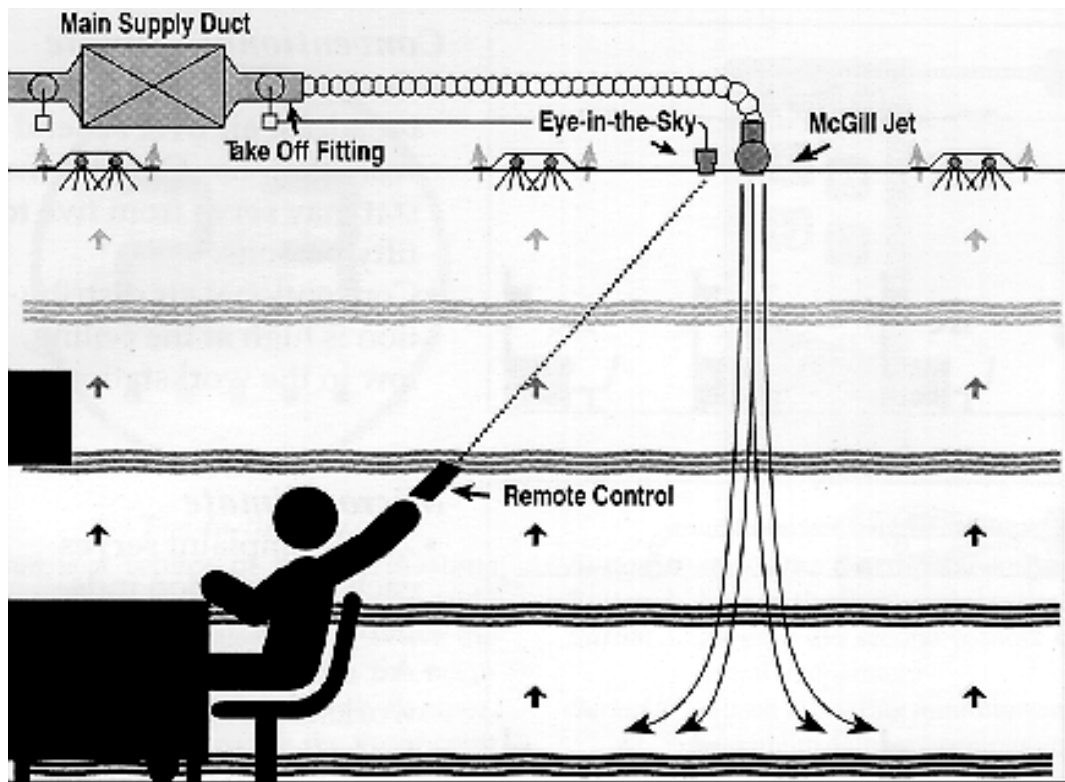


Figure 12. Zero Complaint System (courtesy of Tamblyn Consulting Services)

- Individual Air Outlet; available from Air Concepts, Inc., P.O. Box 31177, Tucson, AZ 85751-1177; telephone: 520-577-2800.
These large nozzles are also installed above each workstation to allow a concentrated column of air to be supplied to occupants or equipment as needed. Airflow direction is adjustable (manually) through $\pm 30^\circ$ from vertical and through 360° rotation about the centerline axis. Air supply volume must be controlled by the overhead air distribution system. Depending on the size of the outlet (four models are available), 8-100 L/s (17-210 cfm) can be supplied at a pressure of 40 Pa (0.16 in. wg).

Japanese Manufacturers of TAC Equipment

Due to the rapid development of TAC systems in Japan during the past decade, a large number of Japanese firms are now manufacturing TAC system products. Floor supply diffusers are the most widely produced products, but several companies are now manufacturing partition-based TAC systems. Associated with underfloor TAC system designs, some Japanese firms are also producing relatively small-sized packaged mechanical units for air handling, outside air treatment, and control. These units are designed with a thin vertical profile and can be serviced from the front, allowing them to be contained within "service system walls." They are downflow units, thereby delivering supply air directly into the underfloor plenum.

Listed below are the leading Japanese manufacturers of TAC equipment. The availability and compatibility of these products outside of Japan is not known to the authors.

- Fujita Corporation, 4-6-15, Sendagaya, Shibuya-ku, Tokyo 151, Japan; telephone: 81-3-3402-1911; desk- and partition-based systems.\
- Kokuyo, 6-1-1 Oimazato-minami, Higashinari-ku, Osaka-shi, Osaka 537, Japan; telephone: 81-6-976-1221; partition-based system for tobacco smoke removal.
- Marumitsu, 4-16-11 Kameido, Koto-ku, Tokyo 136, Japan; telephone: 81-3-5626-7511; floor diffusers.
- Matsushita Seiko Co., Ltd., Ventilation and Air Quality Equipment Division, 6-2-61 Imafuku-nishi, Joto-ku, Osaka, 536, Japan; telephone: 81-6-930-6931; floor and partition-based diffusers, service system walls.
- Naka Corporation, 1-1-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100, Japan; telephone: 81-3-3501-8211; floor diffusers.
- Nittobo, 9-10 Tomizawa-cho, Nihonbashi, Chuo-ku, Tokyo 103, Japan; telephone: 81-3-3669-1413; floor diffusers.
- Obayashi Corporation, 2-2-9 Hongo, Bunkyo-ku, Tokyo 113, Japan; telephone: 81-3-5689-1868; floor diffusers.
- Sinko, 1-4-5 Minamimori-machi, Kita-ku, Osaka-shi, Osaka 530, Japan; telephone: 81-6-367-1811; floor and partition-based diffusers, service system walls.

Discussion

A mail survey of U.S. and some international designers, building operators, and HVAC manufacturers was performed to learn about the current state of TAC systems in the building industry [Bauman et al. 1992]. Based on 65 survey responses, the results showed that individual comfort control was viewed as the single most successful attribute of TAC systems. Numerous respondents suggested that individual control should be considered as a requirement for new offices, not an option, because of the satisfaction produced by control. Surveys of operational TAC systems find that building occupants also rate individual control highly [Spoomaker 1990, Hedge et al. 1992, Kroner et al. 1992, Bauman et al. 1994, Matsunawa et al. 1995].

Another benefit of providing fresh ventilation air in the vicinity of the building occupants is the potential improvement in ventilation performance and indoor air quality in the occupied zone. The increased air motion in the occupied zone can lead to the perception by the occupants that ventilation is adequate. In a related survey, Hedge et al. (1992) have found that the inability of occupants to control environmental conditions is one of the salient factors in reports of Sick Building Syndrome (SBS) symptoms, although there is no direct empirical evidence to support this.

In our laboratory experiments of TAMs and PEMs, we have seen that both systems can be controlled to provide a wide range of thermal comfort conditions in the local workstation environment. In addition, when the supply air jets containing 100% outside air are directed toward the breathing level at a high enough volume, improved ventilation effectiveness can be achieved compared to the case of perfectly mixed air in the office space [Faulkner et al. 1993]. The measured benefit would be smaller in more practical situations in which a substantial amount of return air is recirculated. However, the ventilation effectiveness of TAC systems will still not be any worse than conventional overhead systems, and it is quite likely that occupants will perceive an improvement in air movement and air quality due to the localized air supply outlets.

The effectiveness of local supply units to control comfort will vary depending on the position of the supply outlets in relation to the occupant. Desktop- and partition-based TAC units direct air toward the front and sides of an office worker, typically at desk-level heights and above. Much like the air-conditioning and heating system on the dashboard of a car, this configuration provides quick and efficient response to occupant control. Floor-based TAC units typically deliver air from the side and slightly behind the office worker, with the potential to direct air onto the occupant's legs and ankles, so this configuration is somewhat less effective for individual comfort control.

A perceived disadvantage of supplying air close to the building occupants is the increased risk of draft discomfort. This is one of the main reasons why some engineers refuse to specify such a system. This risk can be largely eliminated by giving occupants control of their local supply unit (they can change the direction or turn the airflow down or off if it is too drafty) and by positioning uncontrolled units sufficiently far from long-term use areas in the office. Alternatively, by using a floor diffuser design that promotes rapid mixing with

the room air, such as the Krantz system, the risk of draft discomfort may be reduced, except within close proximity to the supply outlets.

At maximum air supply rates both the PEM and TAM have the ability to significantly overcool the local environment. While future optimized designs of these and other TAC systems may prescribe reduced peak flow rates, it is important for the supply units to retain some capacity to respond to rare events when rapid cooling is required. The penalty for not being able to satisfy these peak occupant demands can be long-lasting. During our study of ten San Francisco Bay area office buildings [Schiller et al. 1988], we found evidence that office workers remembered extreme conditions when the HVAC system failed to maintain comfort (typically a hot week during the summer) quite clearly and retained a strong negative image of the building system for several months or longer.

Other Task/Ambient Conditioning Products

Because of the significant advantages of using underfloor air distribution with TAC systems, the selection of a raised access floor system is an important consideration. Raised access flooring provides a multiple-use service plenum, serving the distribution needs for power, communication, and HVAC operation (air and water). In modern offices where almost all workstations contain a computer or some other electrical device, cable management has become an increasingly important issue. During a building's lifetime, open-plan offices in particular are often reconfigured (this "churn rate" is estimated to be as high as 30% annually) to accommodate changing tenant needs. For these and other reasons, raised access floors offer advantages and flexibility over other cable management systems. Access floors have been redesigned to be more compatible with office applications. Floor panels are less expensive, lighter weight, carpeted, and can be specially installed to dampen sounds and provide a solid feel underfoot. Although costing higher (\$4 to \$6/ft²) than other cable management options, when combined with underfloor air distribution, the economics quickly improve. In new construction, there is the potential for reduced floor-to-floor heights. Because of the increased space available below the floor for air supply in comparison to a conventional ducted ceiling-based system, it is possible for the overall height of service plenums (underfloor plenum for air supply and most building services plus a smaller ceiling plenum for air return, electric lighting, and fire sprinklers) to be reduced. Some designs may allow the ceiling plenum to be completely eliminated (for example, see McCarry 1995). For additional discussion of many of these issues, see Ellison and Ramsey (1989).

The distributed, workstation-based, configuration of TAC systems makes them well-suited for control applications using occupancy sensors. Occupancy sensors can be used to turn off fan-powered local supply outlets whenever the workstation or local zone is unoccupied. This can be an important energy-saving feature considering the amount of time that office workers are typically away from their workstations (by some estimates, open-plan office workstations in the United States are only occupied on average 50% of the time). Additional energy savings can be realized by putting task lighting and other workstation equipment under occupancy sensor control.

CONTROLS AND OPERATION

Recommendations

1. Local supply outlet temperatures should be maintained above 17°C to 18°C (63°F to 64°F) to avoid uncomfortably cool conditions for the nearby occupant. Furthermore, it is preferable to also maintain the air temperature in the underfloor plenum at no lower than this same temperature to prevent cold floors. As described earlier, when cooler primary supply air is introduced directly into the underfloor plenum, it is very important to ensure that mixing with recirculated air entering the plenum takes place quickly and thoroughly.
2. Due to the importance of individual controls, they should be well designed and convenient to use. While most floor supply units currently on the market are based on manual control (requiring the user to bend down to floor level) it may be advisable to incorporate remote desktop controls to operate the floor units; one such remote-controlled floor unit is described by Matsunawa et al. (1995). It is also advisable to allow switching between local (individual) control and automatic (thermostatic) control as needed.
3. Building operators and occupants who have access to local supply units should be properly trained to allow the operation and control of the TAC system to be optimized.
4. Occupancy sensors provide an effective means of automatically controlling the amount of energy used by the decentralized network of fan-powered TAC supply units. Occupancy sensor performance should be optimized for each application. For example, in partitioned open plan offices, occupancy sensors should be shielded from activation by office workers walking past the workstations. A filter, time-delay, or personal identification strategy may also be used to prevent the sensor from responding to quick visits to an unoccupied workstation.
5. Control strategies for the building's central mechanical system should be well coordinated with the local control units. For example, since most TAC systems are used for cooling applications, if the general office space is overcooled by the ambient air distribution system control strategy, the cool air provided by local supply units will be unwanted by the occupants. By allowing the overall space temperature to rise, local cooling can then be used as needed to satisfy individual comfort preferences.
6. TAC system configurations using fan-powered supply outlets provide a convenient means of allowing direct occupant feedback to improve overall system operation. By monitoring fan speed settings, adjustments can be made to the setpoints for primary supply air temperature, ambient space temperature, and central supply air volume. For example, when a large enough percentage of occupants in the same zone of the building select low fan speeds, indicating that they are too cool, the primary air supply temperature to that zone can be raised. With floor supply outlets, this strategy can help to prevent excessively cool air pooling across the floor, causing potential draft

discomfort [Matsunawa et al. 1995].

7. The building's control system can be configured to allow small-sized control zones as small as individual workstations or areas around a single supply diffuser. These small zones can be controlled based on feedback provided by the occupant's use/control of the local fan-powered supply diffuser, or by a well-placed thermostat. A computer-based control system can also allow these small control zones to be easily combined and reconfigured as needed [Matsunawa et al. 1995].
8. In comparison to TAC system designs using fan-powered supply outlets, pressurized underfloor air distribution systems with floor supply grills tend to provide a more uniform distribution of temperature and air movement throughout the space, but less capability for individual occupant control. Control strategies for these pressurized systems will therefore be closer to conventional approaches that seek to control conditions in a multi-occupant zone based on a single wall thermostat.
9. In underfloor TAC systems, due to the thermal stability created by the large amount of thermal storage in the concrete structural slab, predictive control strategies have been used to estimate the following day's supply air temperature based on the current day's average space temperature. One suggested strategy was to raise tomorrow's supply air temperature by 0.6°C (1°F) when the space temperature did not exceed 21.7°C (71°F) today, and lower tomorrow's supply air temperature by 0.6°C (1°F) when the space temperature exceeded 23.9°C (75°F) today [McGregor 1996].
10. With low-pressure underfloor air distribution systems, special methods may be needed to measure system air flow and to control the VAV operation of the central air handler. In some cases, it may be preferable to control the operation with small-sized floor-by-floor air handling units compared to VAV operation with a larger central AHU.
11. More research is needed to improve overall TAC system performance (e.g., optimize fan speed and temperature setpoints) through methods of control feedback from individual TAC units to the central control system. Research is also needed to improve our understanding of what are the preferred characteristics of individually controlled work environments. Finally, improved engineering guidelines are needed to describe how to effectively utilize the underfloor thermal storage capabilities in TAC system designs.

Discussion

As stated earlier, our industry survey found that occupant comfort as provided by individual control was viewed as the most successful performance attribute of TAC systems [Bauman et al. 1992]. Building occupants are known to place a high value on having some amount of control over their environment. Because of this, it is believed that they will be more tolerant of fluctuating thermal conditions that could reduce costs and energy use. The provision of individual comfort control has the potential to provide certain advantages for TAC systems over other air distribution system designs.

While it is well recognized that building occupants prefer individual control, the extent to which they actually use the local controls, once made available to them, can be surprising. One field survey of several buildings with operational TAC systems found that only 10% of the occupants made adjustments to their controls on a daily basis and one third never used the controls at all [Hedge et al. 1992]. Two recent field studies have similarly found rather limited use of the local controls by the occupants [Bauman et al. 1993, Bauman et al. 1994]. There are a number of possible reasons for this seemingly limited use of the occupant controls. (1) If the ambient space is well conditioned, there may be little need for individuals to fine-tune their local environment. (2) The design of the controls themselves may not be optimized, making their use inconvenient. (3) There may be an upper limit to the role that people prefer to play in the active control of their environment. In other words, there may be a penalty associated with actually having to "do something" to maintain comfort conditions, which could actually increase occupant dissatisfaction [Paciuk (1989)]. (4) Only an occasional adjustment is required because individual preferences are relatively stable. (5) The sense of control may be more important in creating comfort than the actual environmental conditions.

The occupant controls are compared briefly below for four TAC systems discussed above.

1. The floor-based Task Air Module (TAM) can be controlled by reaching down to floor level and adjusting flow direction or fan speed. While these manual controls are simple to perform and quite reliable, it can be awkward for some office workers to reach down to the TAM. The thumb-wheel knob that controls fan speed is difficult to operate and it is not immediately obvious which direction to turn the knob in order to get the desired effect.
2. The desktop-based Personal Environmental Module (PEM) features a more advanced user interface with the multi-function control panel located conveniently on the desk. The control panel is easy to operate and also contains an occupancy sensor, allowing the local unit to be turned off when the workstation is unoccupied.
3. The Krantz underfloor air supply system is generally not configured to allow occupant control, relying instead on the mixing from its diffusers to maintain acceptable thermal conditions in the occupied zone. A throttle ring can, however, be installed in the floor outlets that, when rotated, controls the air flow volume, although not the direction.
4. The Japanese remote-controlled fan-powered floor supply unit described by Matsunawa et al. (1995) allows individuals to conveniently control the fan speed (supply volume) of the floor supply unit. The unit also displays current supply volume to provide immediate feedback to the occupant.

As more task conditioning supply units are developed, the best control characteristics can be utilized. The most effective design solution may be a combination of different supply units and control strategies.

Beyond the development of practical controls for individual TAC supply units, the success of the overall building HVAC system is critically dependent on control issues. Typically, control problems cause a majority of system failures and difficulties. In a TAC system with

occupant control, the design engineer has the responsibility of maintaining control of the overall system performance while "giving up" a certain amount of control to unsophisticated users, a situation that many would choose to avoid. On the other hand, by allowing individual control, the system's ability to provide comfort is enhanced through the use of multiple "human comfort" thermostats. While a normal thermostat responds only to temperature, the human body is a complex integrating instrument, responding to the combined effects of temperature, air movement, radiation, humidity, activity, and clothing level.

It is desirable to provide clear operating instructions for the TAC units to the occupants as well as more advanced training to the building operator. For example, some design specifications encourage individuals to leave their local units on at some intermediate level when they are away from their desk, because the overall system performance depends on the delivery of an adequate amount of air through the TAC supply units.

More advanced controls, such as those included with the desktop PEM, can perform many of these same functions automatically without relying on occupant behavior. Even when the local fan unit is turned off, the main supply line damper is not allowed to close completely and the ducted primary air supply is maintained at a slight positive pressure to ensure that fresh ventilation air is provided at all times. The occupancy sensor also provides important energy savings as discussed further below in *Energy Use*. During our field tests with the PEM units in PG&E's Advanced Office Systems Testbed Project, we noted a few improvements that could be made to the PEM control performance [Bauman and McClintock 1993]:

1. The positioning of the occupancy sensor is critical. If it is in direct view of the entrance to the workstation, a PEM in an unoccupied workstation can be turned on every time someone walks past. In addition to being properly shielded against walk-by turn-ons, the occupancy sensor should also be adjusted (using a filter, time delay, or personal identification) to ignore quick workstation visits, such as a co-worker dropping off some papers in an empty workstation.
2. When the workstation is unoccupied it may be desirable to allow the PEM air supply to completely shut off, provided there is adequate ventilation air being supplied at other locations in the space. If, for example, the PEM units were combined in an office with additional floor-based diffusers that could not be turned off by occupants, these floor diffusers could take care of minimum ventilation rates when large numbers of PEM units were turned off.
3. When an occupant calls for more air flow from the PEM, an improved strategy may be to open the return air damper (pulling air from the kneespace under the desk), thereby providing the requested air flow without having to increase the delivery of primary air.
4. Improvements should be made in the PEM task light dimming control to allow compatibility with a wider range of desk lights now available on the market.

The distributed and decentralized configuration of TAC systems allows improved efficiency in handling part-load conditions that are either localized or occur during off-hours. For example, the load can be met by only activating the necessary fan coil units and the local supply outlets in the affected occupied zone.

In a TAC system involving separate task and ambient subsystems, the design engineer will have to consider several system integration and control issues including the following: (1) What percentage of the building space conditioning load will the task system handle in combination with other more conventional building systems? (2) How does the use of the task system affect supply air flow rates and setpoint temperatures? (3) How does the task system affect fan energy use of the main system? (4) How is the control and operation of the main air handling unit affected by the task system?

Imagawa and Mima (1991) describe one example of a Japanese installation involving a ceiling-based air distribution system for ventilation and ambient space control combined with a separate partition-based task conditioning system that provides cooling and heating with recirculated air. The control sequence is based on the ambient space temperature (T_{amb}). When $T_{amb} > 24.5^{\circ}\text{C}$ (76°F), cooler air is supplied to the task system. When $T_{amb} > 26^{\circ}\text{C}$ (79°F), the ambient system provides additional cooling. When $T_{amb} < 23.5^{\circ}\text{C}$ (74°F), task heating is provided. When $T_{amb} < 22^{\circ}\text{C}$ (71.5°F), ambient heating is also provided. The ambient setpoint is also adjusted based on the percentage of fan-powered task units in use.

Supply volume control of the central VAV air handler requires a different approach with low-pressure underfloor air distribution systems. As previously described, due to the extremely small pressure differentials between the supply plenum and the space, traditional velocity sensors do not provide accurate measurements. An ingenious control strategy proposed by Shute (1992) uses a temperature sensor in the vertical induction shaft connecting the return air at ceiling level to the underfloor plenum. Under normal operating conditions, the floor supply units will be delivering more air to the space than is provided by the central system. In this case, the temperature sensor will measure normal room return temperatures as the air is drawn down the induction shaft to mix with incoming primary air. If, however, the temperature in the induction shaft decreases rapidly, it indicates that the demand for air supply through the floor supply modules has been reduced (i.e., fan units have been turned down or off), resulting in the overpressurization of the underfloor plenum. The central air handler can then be throttled down until the reversal in flow direction through the induction shaft is eliminated.

Future research related to the control and operation of TAC systems is needed to address the following issues:

- Optimization of overall system performance. Due to the limited amount of performance data from operational TAC systems, more field studies are needed to provide additional information on successful operation and control strategies, and occupant response to the TAC system,
- Human thermal preferences for individually controlled local environments. Human subject testing in a laboratory setting is needed to more accurately define thermal

preferences and the limits of thermal acceptability when the subject has some amount of individual control over the local environment, in terms of the following: (1) What is the relative importance to the subjects of the actual local thermal conditions vs. the sense of having individual control over these local conditions? (2) To what extent will subjects tolerate a warmer ambient environment with individual control of local cooling? (3) To what limits will subjects accept asymmetric thermal conditions on their body produced by local air supply and radiant heaters under their personal control? (4) For locally controlled air supply, what are the preferred source locations and configurations, supply directions, air velocities, and air flow patterns (for example, see Fountain 1993 and Fountain et al. 1994)? (5) To what extent will subjects tolerate a thermal environment that is more variable vs. constant over time?

- Thermal performance of underfloor supply air plenums. Experimental and analytical studies are needed to develop improved engineering guidelines for designing and operating a TAC system using an effective thermal storage strategy in the underfloor concrete structural slab.
- TAC system operation in alternative officing installations. Due to rising corporate interest in alternative officing environments, field studies are needed to investigate effective ways to control and operate TAC systems in these highly flexible office configurations.

ENERGY USE

Recommendations

1. With an underfloor air distribution system and the right climatic conditions, take advantage of the extended hours of operation of an outside-air economizer allowed by the higher supply air temperatures. Due to humidity problems in many U.S. climates, however, outside air temperatures above 18°C (65°F) should not be used.
2. Use a 24-hour thermal storage strategy in the exposed structural mass of the floor plenum to reduce peak cooling (and heating) loads, reduce electric utility peak demand charges, and downsize the cooling equipment. Nighttime precooling of the thermal mass can also take advantage of extended economizer operation (under suitable outside air conditions).
3. Space temperature control within the building should be adjusted to realize potentially available cooling energy savings. (1) Due to the increased air movement and controllability provided by the local supply units, maintain higher average space temperatures and allow greater temperature variations (slow drifts) to occur in response to the outside daily cycle. (2) Allow properly controlled thermal stratification to occur using an overall upward flow of air in the space. (3) Use zoning control strategies in which temperature setpoints can be relaxed in less critical building zones, while occupied areas can be well conditioned by the local supply units, if desired by the building occupants.
4. Occupancy sensors should be used to turn off fan-powered local supply units when not in use, provided minimum ventilation rates are maintained within the space. This will minimize the load from local fans and other components.
5. To the extent possible, the central fan should be downsized by taking advantage of reduced static pressures available in an underfloor plenum supply configuration, by minimizing the amount of air delivered by the central fan (e.g., supply only minimum required outside air quantity), and relying on the local fan units to provide the necessary air exchange in the space.
6. Water-based fan coil units and heat pumps may be the most energy efficient approaches to handling the extreme cooling and heating loads that occur only occasionally and at specific locations (e.g., perimeter zones) in the building.
7. The efficiency of local fan motors should be improved and incorporated into future designs of local supply units.

Discussion

There are many factors that can affect the energy performance of TAC systems. Responses to our industry survey [Bauman et al. 1992] indicated that opinions were fairly evenly split regarding the energy use of a TAC system in comparison to a conventional

system; 32% stated that energy use would be somewhat or greatly improved, 28% roughly equivalent, and 22% somewhat worse. It was also felt that energy performance would be application-specific, further evidence of the uncertainty associated with trying to generalize about overall energy use. Not surprisingly, energy use was identified as one of the top three issues concerning TAC systems that would warrant further research. In the literature, only a few studies of energy use of TAC systems are reported. Two earlier computer modeling studies concluded that installations may use either more or less energy compared to a conventional air distribution system depending primarily on operating strategies [Heinemeier et al. 1991, Seem and Braun 1992].

In a more recent study, annual building energy simulations using DOE-2 investigated the energy performance of a prototypical office building in two California climates, Fresno and San Jose [Bauman et al. 1994]. The simulations compared three different TAC system configurations versus a base case building consisting of a reasonably efficient standard overhead air distribution system with an air-side economizer. The operation and control strategies that proved to have the greatest energy impact were (1) use of an air-side economizer, (2) increased throttling range (up to 4°C [7°F]) for space temperature control allowed by the individual controllability of the TAC systems, (3) increased stratification (up to 2.5°C [4.5°F]) in the space produced by the floor-to-ceiling air distribution of the TAC systems, and (4) nighttime precooling of the building thermal mass in the underfloor plenum by fan-driven ventilation. The simulation results showed that, in comparison to the base case, a desktop-based TAC system with occupancy sensor control and the first three of the above strategies in a San Jose office building could save annually as much as 18% of the cooling energy, 18% of the distribution (fans and pumps) energy, 10% of the total electricity, and 9% of the total electricity cost. When nighttime ventilation was added, the cooling energy savings increased to 23%, but distribution energy increased to 2% above the base case due to the nighttime operation of the fans. In this latter case, although total electricity use was slightly higher (9% lower than the base case), total electricity costs remained the same (9% below base case) because of the further reduction in peak demand provided by the nighttime ventilation strategy.

Despite the above described potential energy savings, as with any new technology it is possible to operate a TAC system in an energy inefficient manner. An example of this is described by Bauman et al. 1994, who conducted a field study of a floor-based TAC system in an engineering office building. The system being studied consisted of fan-powered floor supply modules with the underfloor air supply plenum being served by a variable-air-volume (VAV) central air handling unit (AHU). Although the recommended operating procedures called for the underfloor plenum pressure to be maintained at a zero or slightly negative pressure with respect to the occupied space, the building operators were unable to control the AHU at these low pressures, and instead were maintaining a constant higher pressure across the VAV box serving the underfloor plenum. As a result, the underfloor plenum was overpressurized, leading to excessive central fan energy use (estimated to be 10 W/m² [0.9 W/ft²]), excessive air flow into the space, and overcooled conditions for some occupants. The overcooled conditions had in turn led to a situation in which many occupants did not want any airflow from their floor supply modules, and only about one-third of these floor supply units were in use. It was estimated that by reducing the central AHU air supply volume, improving the integration of the AHU and floor supply

modules, and turning fans down or off during low-load periods, annual total fan energy use could be reduced by more than 60%.

At first glance at the energy performance issue, the major disadvantages of occupant-controlled TAC systems compared to conventional systems are: (1) with fan-powered local supply units, the operation of many small individual fans; and (2) the fact that individuals are allowed to control these supply units to optimize their personal thermal comfort without regard for the energy performance of the overall system. The first is the result of switching from a more conventional centralized design to a decentralized design. The second involves the integration of the TAC system with the total HVAC system. Both of these topics are discussed briefly below.

The small fans contained in the controllable TAC supply units are less efficient than the large fans used in a centrally-controlled system. In more complex TAC units, such as the Johnson Controls PEM, additional electrical energy is consumed by the electronic controls and the radiant heating panel (when in use). On the other hand, the Krantz underfloor air supply system does not use fan-powered supply units and in this way resembles a centrally-controlled system. Central fan energy use will be correspondingly higher in this case.

The fan efficiency of the fan-powered floor-based supply module (e.g., Tate's TAM) is currently on par with that of relatively efficient ceiling-based parallel fan-powered mixing boxes (FPMB) (0.54 W/l s^{-1} [0.27 W/cfm]). However, unless series FPMBs are installed in a conventional system, FPMBs do not need to operate continuously or as often as a TAC supply unit at an occupied workspace. Normally, parallel FPMBs are operated only when needed (e.g., on a call for heating in perimeter zones of the building). Clearly, an effective strategy will be to minimize to the extent possible the local fan load in a TAC system.

In an underfloor air distribution system, significant reductions in central fan static pressure can be realized, thereby conserving central fan energy in comparison to a ducted system. In addition, if a large amount of return air from the room is drawn into the sub-floor plenum to be mixed with incoming primary air, the low resistance and short path length required for this process can translate into savings in fan energy compared to a conventional system that recirculates air all the way back to the central air handling unit. Spoormaker (1990), who has successfully installed numerous TAC systems using fan-powered floor supply modules, claims to be able to meet the cooling load in the interior zone of an office building with a total fan load (central plus local) that is 56% of the required central fan load of a comparable all-air ceiling distribution system. In his calculations, although the local fan load is approximately 4 W/m^2 (0.4 W/ft^2), the central fan load for the TAC system is reduced to 1.5 W/m^2 (0.14 W/ft^2) by handling only the quantity of outside air required to maintain minimum ventilation rates.

In terms of the occupant control issue, it can be said that in any situation where building occupants are uncomfortable they will often take matters into their own hands. In a building with a centralized air distribution system, these dissatisfied occupants may operate desk fans or electric heaters to satisfy their needs. By providing controllable supply units, a TAC system may in fact provide some improvement over this rather random approach. In addition, by providing occupancy sensors to turn off local units when

they are not needed, significant reductions in energy use can be obtained for many office occupancy patterns. Based on field measurements of the PEM, Bauman et al. (1993) estimated that such an arrangement could save up to 30% of the local fan and lighting energy used during the course of a typical work day.

As discussed earlier in *Controls and Operation*, the provision of individual control and increased air velocities can lead to reductions in equipment costs and energy use for cooling applications, because the occupants will be more tolerant of higher average room temperatures and of a greater daily variation in temperature related to the outside diurnal cycle.

Other temperature control strategies with TAC systems can also result in cooling energy savings compared to a conventional system. Thermal stratification produced by an upward movement of air in the space, if properly controlled, can result in cooling energy savings of as much as 15% [Shute 1992]. In this situation, the temperature of the space above the occupied zone can be allowed to increase, as some of the warm air generated by space heat loads reaches the ceiling-based return location without being completely neutralized by the incoming supply air.

As previously described in *Task/Ambient Conditioning System Design*, under the right climatic conditions, an underfloor air distribution system allows the implementation of a 24-hour thermal storage strategy using the mass of the building structure exposed to the air flowing through the plenum. By precooling the thermal mass during the nighttime, peak cooling demand can be partially offset during the following day. Spoomaker (1990) has estimated that such a strategy can reduce peak instantaneous cooling loads in interior zones of office buildings by as much as 40%. Shute (1995a) estimates that thermal storage effects are approximately 30% of a typical daily cooling load. This 24-hour thermal storage strategy also extends the hours that an outside-air economizer can be used due to the cooler nighttime temperatures. Under winter conditions, the thermal storage can also be used to assist nighttime heating, if required, by recovering heat stored in the mass during the previous day's cooling cycle. Additional research is needed to more precisely quantify the potential benefits of using thermal storage in the structural slab and to provide guidelines for the design and operation of underfloor air distribution systems using such a strategy.

DESIGN AND CONSTRUCTION

TAC systems require good coordination between all building trades throughout the design and construction process, particularly if using an underfloor air distribution system. Shute (1995a) provides an excellent list of recommendations for the design and construction of underfloor air distribution systems. McCarry (1995) and Blaevoet (1995) also describe some guidelines based on their experiences with underfloor TAC system installation. Shown below is a partial list of recommendations for design and construction.

- It is essential that the implications of the raised access floor be considered early in the design process.
- The concrete slab surface must be sealed to reduce dust, and the underfloor plenum and floor panels must be thoroughly cleaned both during installation of the access floor and again before occupancy.
- The height of the access floor and the placement of the 0.6 m x 0.6 m (2 ft x 2 ft) raised floor pedestal grid is critical with respect to locating all underfloor service installations.
- It is important to lay out underfloor equipment requiring regular maintenance to be located in accessible areas, such as corridors, not underneath furniture and partitions.
- In partitioned office spaces, offset the partition grid from the floor grid so that partitions do not cover joints between floor panels, thereby preventing access to the underfloor plenum on both sides of the partition.
- Consider dead load allowance and seismic bracing of the access floor.
- Determine areas in the building with no access floor and allow for transitions to areas with access flooring.
- In pressurized underfloor air distribution systems, greater care must be taken during construction to seal the underfloor plenum to prevent uncontrolled air leakage.
- Designers must consider that fan rooms or access for HVAC distribution will be required at more frequent intervals than with conventional air distribution systems.
- If called for, return air shafts must be designed between the ceiling and the underfloor plenum, usually around columns or other permanent building elements.
- The main structural slab, the traditional working platform, will not be available continuously during construction, and therefore a well-coordinated construction sequence is necessary (see Shute 1995a).
- In retrofit jobs, special consideration should be given to the installation of TAC supply units within a person's work area. The occupants should be well-informed of the proposed design and placement of the supply outlets and controls, to avoid unnecessarily upsetting them as the result of a perceived thoughtless intrusion into their personal workplace.

SYSTEM COSTS

Recommendations

It is recommended that the costs of TAC systems be evaluated over the building's lifetime, including first costs, maintenance and operating costs, space changeover costs, and the potential cost savings associated with improved thermal comfort, ventilation effectiveness, and worker productivity. In order to complete such a life-cycle economic analysis, more research is needed to quantify the effects of providing individual control and improved building environmental quality on worker productivity.

Discussion

As described earlier, the costs associated with installing, operating, and maintaining a building's HVAC system play a critical role in the selection process. The results of a recent survey of industry perspectives on TAC technology demonstrate the importance of cost considerations to the building industry [Bauman et al. 1992]. This survey found the perceived higher cost of TAC systems to be one of the two top reasons that TAC technology is not used more widely by the industry today (the other reason is a lack of information and experience). On the other hand, the perceived beneficial features of TAC systems can help to offset the negative impact of increased costs. For example, a majority of the survey respondents felt that occupant comfort (83%), worker productivity (62%), and indoor air quality (54%) were improved for a TAC system compared to a conventional system. Correspondingly, a majority of the survey respondents also indicated that equal or higher costs of TAC systems compared to conventional systems are justified by improved comfort (80%), productivity (68%), and air quality (64%).

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 amount of this increase can be minimized and in some cases completely offset by savings in installation costs for ductwork and electrical services, as well as from downsizing of some mechanical equipment. Based on previous experience, one design engineer describes how he can break even in first costs for a pressurized underfloor air distribution system compared to a conventional overhead system by using the following rule of thumb: cost of underfloor air system (raised access flooring and floor supply outlets) = \$8/ft²; cost savings in ductwork = \$6/ft²; cost savings in electrical services = \$2/ft² [Blaevoet 1995]. For TAC systems with individual fan-powered supply units, initial equipment costs are expected to be somewhat higher than centralized systems or TAC systems without local fan units. In an economic analysis by York (1993), adding an access floor to a conventional 9,300-m² (100,000-ft²) building increases its first cost by 2.4%. However, if the underfloor plenum is used for air distribution with fan-powered floor diffusers, the first cost of the building is increased by only 1.4% over the baseline. As described earlier, another important first cost consideration in new construction is that underfloor air distribution can lead to reduced floor-to-floor heights.

Since TAC systems still represent a new and unfamiliar technology, a designer may incur added up-front costs associated with selling the idea of TAC technology to the client and

developing the building design. Utility incentive programs, if available, could help to compensate designers of energy-efficient TAC systems for any higher first costs during the design phase of a project.

Operating costs for TAC systems can be reduced in accordance with the energy-saving strategies discussed above in *Energy Use*. With the improved thermal comfort and individual control provided by TAC systems, occupant complaints requiring response by facility maintenance staff can be minimized. This can be a significant savings as evidenced by recorded complaint data from the corporate headquarters of the West Bend Mutual Insurance Company -- a new office building occupied in 1991 in which 370 desktop TAC units were installed. In comparison to the previous headquarters building, hot/cold calls were reduced from an average of 40 calls per month to only 2 calls per month [Lomonaco 1996]. Other operation and maintenance cost savings that can be achieved with underfloor air distribution include (1) lower labor costs resulting from working at floor level instead of on ladders at ceiling level, and (2) lower air balancing costs due to the similar pressure conditions at supply diffuser locations provided by an underfloor air supply plenum.

Some maintenance costs of underfloor TAC systems may increase in comparison to conventional overhead systems. For example, equipment maintenance costs associated with the moving parts and larger number of distributed units may increase for systems using fan-powered supply units. Another maintenance issue to consider is the location of underfloor mechanical equipment, such as fan-coil units. In buildings with frequent furniture moves, it is important to maintain free access to the panels above these underfloor units. The key items (if present) requiring maintenance include (1) coil cleaning, (2) condensate pan cleaning, (3) fans, and (4) changing filters (a 3-6 month service cycle is recommended).

Underfloor TAC systems using raised access flooring provide maximum flexibility and significantly lower costs associated with reconfiguring air supply locations and other building services to adapt to the changing requirements of existing or new tenants over the lifetime of the building, and thus reduce life-cycle costs substantially. This flexibility can be especially important over the lifetime of buildings having high churn rates. It is estimated that approximately one-third of U.S. commercial office spaces get reconfigured each year [York 1993]. Assuming a 30% churn rate, York estimates 5-year life cycle costs for an intelligent building containing an underfloor TAC system and advanced lighting to be 7% lower than that for traditional buildings. York's analysis reveals the significant operational cost advantages of such an intelligent building design over traditional buildings -- the annual operational costs alone are estimated to be only 8% of those for the traditional building. Blaevoet (1995) assumes a 15% churn rate in his life-cycle cost model which predicts a 2.7% reduction in 5-year life-cycle costs for a pressurized underfloor TAC system compared to traditional designs. Shute (1995b) presents actual cost data from a completed project showing a 5% reduction in 5-year life-cycle costs for a low-pressure underfloor TAC system with fan-powered floor supply units compared to the estimated cost if a conventional VAV system had been installed in the same building.

Probably the most attractive feature of TAC systems is the provision of individual control and the potential for individual workers to maintain a high quality work environment of their choice. Although it is difficult to quantify, there is a growing belief that actual and perceived improvements in environmental quality can lead to increased worker satisfaction and productivity. The financial implications of improving productivity by even a small amount have the potential to be very large as salary costs typically make up at least 90% of all costs (including construction, operation, and maintenance) over the lifetime of a building. Nationwide, a mere 1% increase in worker productivity would translate into a potential annual cost benefit of \$25 billion. In today's competitive world economy, a company's employees make up its most valuable economic assets. Protecting and improving the productivity of these employees will have a strong influence on future investments. One of the first major studies of productivity used self-assessed job performance to conclude that improved thermal comfort and worker satisfaction can lead to increased worker productivity [Brill and Margulis 1984]. Wyon (1996) estimates that even under the conditions of thermal neutrality with the environment, the provision of individual control of local cooling and heating equivalent to $\pm 3^{\circ}\text{C}$ (5°F) can improve group work performance by 3-7%, depending on the nature of the task. This is because the average neutral temperature cannot satisfy all occupants, whose individual thermally neutral points vary substantially. If the room temperature is raised above thermal neutrality, Wyon estimates the performance improvement to be significantly higher. Most of the currently available fan-powered TAC supply outlets provide individual control of local temperatures over this same $\pm 3^{\circ}\text{C}$ range. A recently completed field study of the first large installation of Johnson Controls PEM (desktop) units in a new office building has concluded that the PEM system was responsible for a 2.8% increase in worker productivity [Kroner et al. 1992]. In this case, assuming that the average worker salary was \$30,000 and the cost of each PEM unit was \$1,200, the payback period for the PEMs would be only 1 1/2 years.

Looking to the future, more research is needed to improve our understanding of what impact the provision of individual control and improved building environmental quality has on worker productivity. Due to the recognized difficulty in quantifying productivity in today's largely knowledge-based work environment, innovative research approaches must be devised to address this issue of critical economic significance.

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