Title

How low can you go? air flow performance of low-height underfloor plenums

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SUMMARY REPORT

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IN THIS REPORT

"HOW LOW CAN YOU GO?"
AIR FLOW PERFORMANCE OF LOW-HEIGHT UNDERFLOOR PLENUMS

FRED BAUMAN, P.E., PAOLO PECORA, AND TOM WEBSTER, P.E.

EXECUTIVE SUMMARY

Underfloor air distribution offers several potential advantages as a method of delivering space conditioning in commercial buildings. This technology has proven to be the most effective method of delivering conditioned air to localized diffusers in the occupied zone of the building. Localized distribution of conditioned air, particularly when occupants are given individual control of the incoming air, is a key component of the more flexible office arrangements required for the office of the future. Underfloor air distribution also makes use of a plenum space that allows for the readily accessed and modified cabling required to accommodate today's information technology. In practice, there is great interest in limiting the height of underfloor plenums to increase their feasibility for renovation work.

CBE is developing design and specification guidelines for configuring and operating underfloor plenums as part of an intelligent approach to underfloor air distribution technology. This report summarizes results from the first phase of this project, where full-scale empirical testing was used to investigate plenum configuration issues, including minimum plenum height, for which acceptable air flow performance can be achieved in a pressurized underfloor plenum. Air flow performance was measured in terms of the ability of the underfloor air supply plenum to uniformly distribute air to all floor grills for a given air supply volume and plenum configuration. This determination is a critical factor affecting the wider use of underfloor air distribution in both new and retrofit construction.

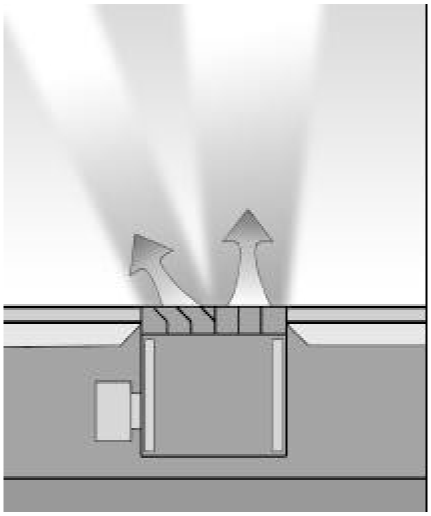


FIGURE 1 *Using conventional air handling equipment, conditioned air is delivered through the underfloor plenum to the occupied zone of the building. (Image: York International Corporation)*

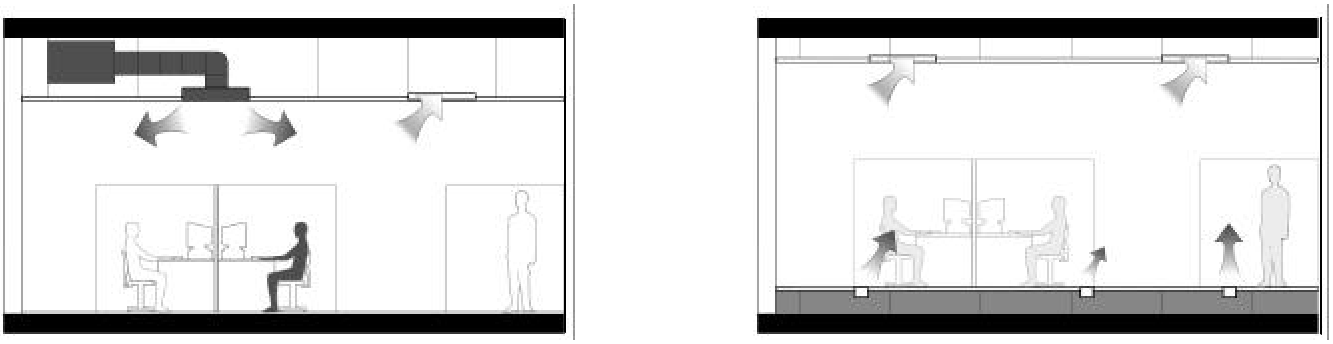
In April 1998, CBE researchers set up a full-scale underfloor air supply plenum test facility in a 40-foot by 80-foot (12-m by 24-m) unoccupied open-plan area with an 8-inch (205-mm) raised access floor (7 inches [180 mm] of clear space) in a large office building. Air was supplied into the plenum at two points along one 40-ft edge, and up to 32 rectangular floor grills, evenly distributed across the plenum, served as the air supply outlets from the plenum to the room. Three plenum heights were investigated (7-inch [180-mm], 3-inch [75-mm] and 2-inch [50-mm] clear space) under a range of air supply volumes, obstruction conditions, and other plenum configurations. Five separate week-long field experiments were conducted in the test facility between April and December 1998. Each test was performed under steady-state conditions and the following measurements were made: (1) supply volume into the plenum at the fan inlet duct, (2) static pressures and air velocities in the plenum, and (3) supply volume delivered to the room using a flow hood at each floor grill.

The major conclusions are as follows:

1. **In specifying the height of an underfloor air supply plenum, CBE recommends that, on average, at least 3 inches of clear space for air flow be provided in addition to the height required for other factors.** Air delivery through floor outlets from a pressurized plenum with 7 inches of clear space is very uniform over a full range of typical air supply volumes (0.5 to 1.5 cfm/ft^2 [2.5 to 7.6 L/(s·m^2)]), even at a distance of 80 feet (24 meters) from the plenum inlet. Air delivery through floor outlets from a pressurized plenum with 3 inches of clear space varies by no more than 10% from the average up to air supply volumes of 1.0 cfm/ft^2 [5.1 L/(s·m^2)], even at a distance of 80 feet from the plenum inlet. Air delivery through floor outlets from a pressurized plenum with only 2 inches of clear space is significantly influenced by the increased resistance to flow within the plenum. However, the maximum average magnitude of these variations from uniform air flow (25-30%) may be small enough to not exclude the use of extremely low-height underfloor plenums under certain conditions.

2. **Solid obstructions, even with only 1.5 inches (38 mm) of clear space above them, may be located in a plenum with at least 7 inches of clear space and have very little impact on the overall air flow performance.** In plenums with only three inches or less of clear space on average, obstructions cause a more significant degradation to the uniformity of air flow distribution.

FIGURE 2 *Underfloor air distribution can provide building occupants with control over temperature and air flow. (Image: Tate Access Floors)*



Conventional Overhead Air Distribution

Underfloor Air Distribution

FIGURE 3 Underfloor air distribution delivers conditioned air to the workspace where it is needed. The upward air movement flows in the same direction as the thermal buoyancy produced by computers, task lighting and people. Warm and stale air is directed to ceiling returns and extracted, leaving the workspace conditions more desirable for human comfort.

3. **If one or two floor panels are removed for service or repair work, the amount of air delivered to floor outlets in that same zone may be reduced by up to 50%.** However, given that the uniformity of air flow delivered through the floor outlets across the zone is relatively unchanged, this situation may be acceptable on a short-term basis.

4. **At the primary air inlet to an underfloor plenum, air may be delivered horizontally or vertically with little impact on the air flow performance in a plenum with at least 7 inches (180 mm) of clear space.**

5. **Although increasing the number of outlets in a single plenum zone would be expected to improve the uniformity of air flow distribution, no significant degradation in performance was observed when the number of outlets was reduced by 50% in both 3-inch (75-mm) and 2-inch (50-mm) plenums at a nominal air flow rate of 1.0 cfm/ft^2 (5.1 L/(s·m^2)).**

6. **To apply the findings of this study in practice, an important consideration will be the thermal performance, or variations in supply air temperature across the area of the plenum**. Depending on conditions at the time, if heat transfer from/to the concrete slab and other surfaces in the plenum results in supply air temperatures that are either too high or too low, the thermal environment of the room may deteriorate, particularly at large distances from the plenum inlet. An upcoming phase of this project will address thermal performance issues.

1 INTRODUCTION

In today's competitive office market, building owners, designers, and facility managers are seeking up-to-date information about new technologies, design approaches, and products that can improve the value of their buildings. Underfloor air distribution is a method of delivering space conditioning in commercial buildings that is increasingly being considered as a serious alternative to conventional ceiling-based air distribution systems because of the significant benefits that it can provide. While underfloor systems have achieved some acceptance in South Africa, Germany and other parts of Europe, and most recently in Japan, growth in North America has been relatively slow up until the last few years. As with any new and unfamiliar technology, resistance to wider use is driven by the perceived higher risk to designers and building owners, perceived higher first costs of raised flooring, and a lack of available information in the form of standardized design guidelines.

The installation of raised access flooring with an underfloor air distribution system is most easily achieved in new construction. 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. An integrated design can, in fact, lead to reduced floor-to-floor heights. Some designs may allow the ceiling plenum to be completely eliminated [1]. However, the feasibility of adding a raised floor with a typical height of 12-18 inches (0.30-0.46 m) during a renovation project is severely restricted in the large majority of buildings having limited floor-to-floor heights. This CBE project was initiated to develop design and specification guidelines for configuring and operating underfloor air supply plenums. During the first phase of work reported here, full-scale empirical testing was used to investigate the minimum plenum height, as well as other practical performance issues, for which acceptable air flow performance can be achieved. This determination is a critical factor affecting the wider use of underfloor air distribution technology in both new and retrofit construction.

2 BACKGROUND

Originally introduced in the 1950s in spaces having high heat loads (e.g., computer rooms, control centers, and laboratories), and subsequently introduced in office buildings in the 1970s, underfloor air distribution uses the open space (underfloor plenum) between the structural concrete slab and the underside of a raised access floor system to deliver conditioned air directly into the occupied zone of the building through a variety of supply outlets located at floor level or as part of the furniture and partitions. There are two primary system types for underfloor air distribution installations: (1) pressurized plenum in which the central air handler under variable-air-volume (VAV) or constant air volume (CAV) control forces air out of supply grills or diffusers mounted in the access floor panels or elsewhere; and (2) zero or slightly negative-pressure plenum in which low-powered local fans (under occupant or thermostatic control) work in combination with the central fan (under VAV or CAV control) to draw air out of the plenum and into the occupied space. Other ducted arrangements are possible, but the above two configurations are the focus of this study because they provide certain energy and cost benefits by allowing the supply air to flow freely through the underfloor plenum.

Research results directly related to the air flow performance of pressurized, low-height underfloor plenums were found to be only available in a series of Japanese papers. A summary paper describes the results of tests conducted in a scale model of an underfloor plenum (simulated heights of 11.8 inches (300 mm) and 4.7 inches (120 mm)) and in a full-scale office space with a very low-height (1.3 inches (34 mm) of clear space) plenum [2]. The authors estimated that the rate of air delivery through the floor outlets varied by about a factor of two across the 2,900 ft^2 (270 m^2) full-scale office space when air was supplied at a rate of 2,000 cfm (940 L/s), or 0.7 cfm/ft^2 (3.5 L/(s·m^2)), through a single inlet at the edge of the space. This degree of variation may be too large for acceptable performance in an office.

As more underfloor air distribution installations have been completed in recent years, the experience and knowledge-base with these systems have grown. Research results as well as occupant and performance data from case studies are now available demonstrating that a well-designed underfloor air distribution system can provide improved thermal comfort, ventilation and indoor air quality, and occupant satisfaction and productivity at first-costs and energy use similar or lower than conventional systems. Some of the more significant research findings are discussed briefly below.

Occupant thermal comfort is perhaps the area of greatest potential improvement in underfloor air distribution systems because task/ambient conditioning (TAC) is a natural extension of the system design. TAC systems deliver air through outlets in the near vicinity of the building occupants and are uniquely characterized by their ability to allow individuals to have some amount of control over their local thermal environment. Recent laboratory tests show that commercially available

TAC supply outlets provide personal control of equivalent whole-body temperature over a sizable range: up to 9°F (5°C) for floor-based TAC outlets [3]. This amount of control is more than enough to allow individual thermal preferences to be accommodated.

Studies of desktop TAC systems augment these findings. Reference [3] shows that desktop TAC outlets can provide up to 13°F (7°C) of control of equivalent whole-body temperature. In a complementary series of ventilation performance tests using the same laboratory setup as the above study, significant improvements (over well-mixed conventional systems) in the air change effectiveness at the occupant's breathing level were measured for two desktop TAC systems supplying 100% outside air at low flow rates [4].

Field measurements and occupant surveys taken before and after the installation of a desktop TAC system showed significantly higher satisfaction with the temperature level and temperature control for the occupants who received a desktop TAC unit compared to a control group of those who did not receive such a unit [5]. Another well-known field study of desktop TAC units with underfloor air distribution concluded that the desktop TAC system was responsible for a 2.8% increase in worker productivity [6]. A recent analysis of previous research indicates that individual control of local cooling and heating equivalent to ± 5°F (3°C) can improve group work performance by 3% to 7%, depending on the nature of the task [7].

A well-engineered underfloor air distribution system designed to handle the dominant cooling loads in interior zones of office buildings has several energy-conserving features. Due to extremely low operational static pressures in underfloor air supply plenums (typical pressures are 0.1 in. H_20 (25 Pa) or less), central fan energy use can potentially be reduced relative to traditional ducted overhead air distribution systems depending on the design strategy adopted (see [8] for a more complete discussion of this issue). Annual building energy simulations have estimated that an office building in the San Francisco Bay area with underfloor air distribution and a desktop TAC system using several intelligent control strategies can save as much as 18% of the cooling energy, 18% of the distribution energy, and 10% of the total electricity in comparison to a conventional system [9].

Underfloor systems are typically controlled to deliver higher temperature air (above 63-64°F [17-18°C]) through the supply outlets due to their close proximity to the occupants. Under the right climatic conditions, this allows extended hours of operation of an outside-air economizer. Using a 24-hour thermal storage strategy in the exposed concrete slab of the floor plenum, peak cooling loads can be reduced, cooling equipment can be downsized, and nighttime precooling of the thermal mass can take advantage of extended economizer operation. Reduction in the summer peak demand using thermal storage is estimated to be as high as 30% [10].

First costs for underfloor air distribution systems will usually, 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. The first cost of installing a raised access floor is most commonly justified on the basis of improved cable management in today's modern office, and in particular the increased flexibility and lower costs associated with reconfiguring building services in buildings having high churn rates. This flexibility can significantly reduce life-cycle building costs [11-13].

Several authors have described design and operating guidelines for underfloor air distribution systems [1, 10, 13-15]. For additional reading, please refer to these references.

3 EXPERIMENTAL METHOD

The technical approach used in this study was to conduct a series of experiments in a full-scale underfloor air supply plenum test facility. The objective of the experimental program was to provide answers to a series of very practical questions about the air flow performance of pressurized, low-height, underfloor air supply plenums, including the following:

- What is the minimum plenum height at which acceptable air flow performance can still be achieved?
- What is the effect of obstructions (e.g., cables, ducts) on air flow performance in low-height underfloor plenums?
- What is the maximum floor area that can be adequately served using a single primary air inlet location to the plenum?

These and other questions influenced our design of the experiment to cover a wide range of test conditions to "push the envelope" of commonly used rules of thumb for acceptable performance. It was hoped that the empirical data collected from these experiments would help identify practical limits for acceptable performance.

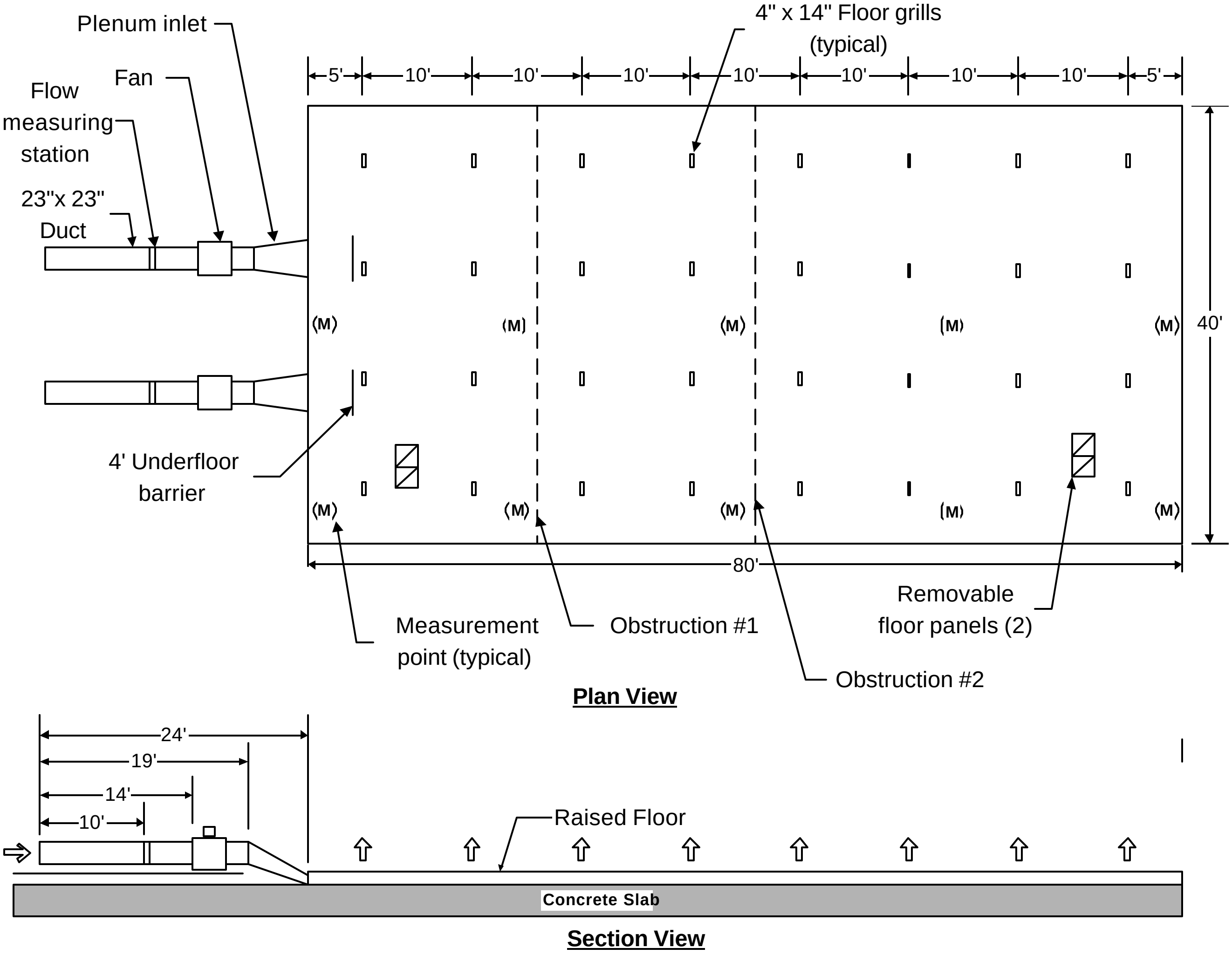


FIGURE 4 Plan and section views of 32-outlet CBE Underfloor Air Supply Plenum Test Facility at Bank of America/Brea

Figure 4 shows plan and section views of the 40-ft (12-m) by 80-ft (24-m) underfloor air supply plenum test facility, that was set up in a large unoccupied space of an open plan office building in southern California. The test area had an existing 8-inch (205-mm) raised access floor (slab to finish floor height) producing approximately 7 inches (180 mm) of clear space between the concrete slab and the underside of the floor panels. The perimeter edges of the test area were sealed with a combination of plastic sheeting and duct tape. Air was supplied horizontally into the plenum along one 40-ft edge of the plenum by two centrifugal inline fans with one-hp variable speed motors. A variable frequency drive controlled the two fan motors in parallel, allowing a range of air supply volumes into the plenum to be investigated. As shown in Figure 4 and the photo in Figure 5, the fan/inlet duct configuration included a flow measurement station that provided an accurate measure of the flow being supplied into the plenum.

Rectangular 4-inch by 14-inch (100-mm by 360-mm) floor grills served as the air supply outlets from the plenum to the room (Figure 6). Although these grill designs do not represent typical floor diffusers found in office installations, as discussed later, the adjustable dampers were used to increase the flow resistance of the grills to a more representative value. For most of the tests reported here, 32 floor grills were evenly distributed across the 3,200 ft^2 (300 m^2) test area. As shown in Figure 4, this arrangement produced 8 rows of 4 grills each to cover the test area. Under the commonly used air supply volume of 1 cfm/ft^2 (5.1 L/(s·m^2)), each grill would deliver 100 cfm (47 L/s), matching typical floor outlet design flow rates.

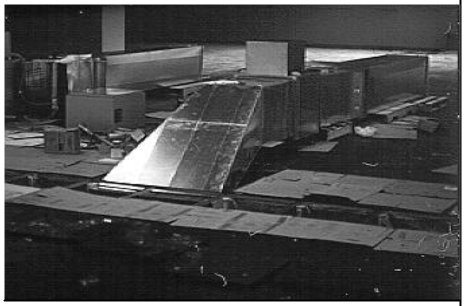


FIGURE 5 *Photo of supply fan and inlet duct at CBE Underfloor Air Supply Plenum Test Facility*

All experiments measured the ability of the underfloor air supply plenum to uniformly distribute air to all floor grills for a given air supply volume and plenum configuration. Each test was conducted under steady-state conditions and the following measurements were made (with the following instrumentation): (1) supply volume into the plenum (flow measurement station at fans); (2) air supply volume into room (flow hood at each floor grill); (3) plenum static pressure relative to room pressure (digital micro-manometer with pitot tube at ten measurement points shown in Figure 4); and (4) plenum air velocities (hot wire anemometer at ten points shown in Figure 4).

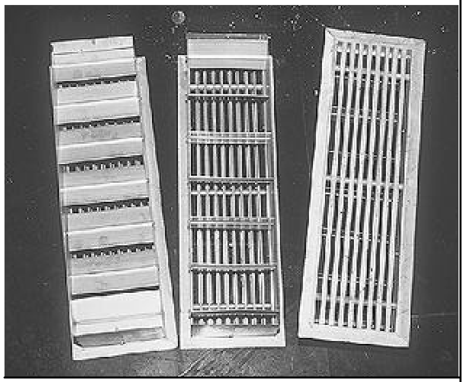


FIGURE 6 *Photo of floor grills. From left to right: bottom view with dampers partially closed, bottom view with dampers open, and top view*

All instrumentation was either new (flow measurement station) or calibrated prior to use [16]. The flow measurement stations mounted in the straight ducts upstream of the fans each measured the air flow volume to within 8 cfm (3.8 L/s) (manufacturer's specified accuracy), corresponding to an error of only 1% at the lowest flow rate tested (0.5 cfm/ft^2 [2.5 L/(s·m^2)]). The micro-manometer agreed to within 6% of a high precision liquid manometer over the range of pressures measured in this study. The hot-wire anemometer had a manufacturer's specified accuracy of 3% of the reading ±20 fpm (0.1 m/s). The flow hood was calibrated twice: once in our laboratory and once by the manufacturer. The interpretation of the flow hood data is discussed further below.

4 TEST CONDITIONS

Three plenum heights were investigated: 7-inch (180-mm), 3-inch (75-mm), and 2-inch (50-mm) clear space. Beginning with the original plenum (7 inches of clear space), expanded polystyrene blocks were installed to reduce the effective plenum height to 3 inches, and later to 2 inches (see Figure 7). For each plenum height, a range of air supply volumes, obstruction sizes, and other plenum configurations were investigated. The complete list of test conditions is shown in Table 1.

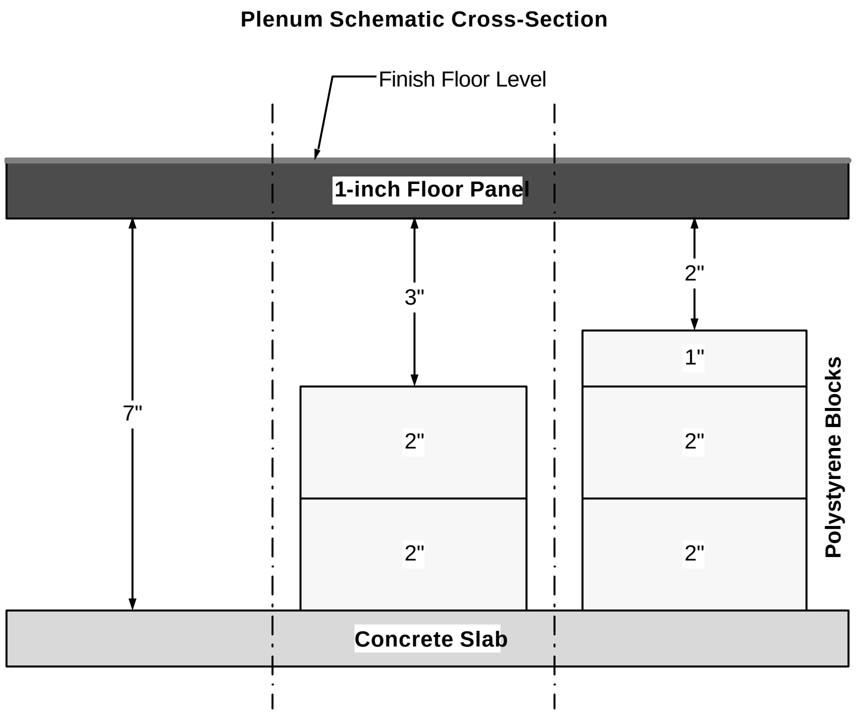


FIGURE 7 Schematic cross section of CBE Underfloor Air Supply Plenum Test Facility

TABLE 1 TEST CONDITIONS

PARAMETER	RANGE
1. Height of clear space in plenum	7 inches, 3 inches, 2 inches (180 mm, 75 mm, 50 mm)
2. Total supply volume into plenum	0.5, 1.0, 1.5 cfm/ft^2 (2.5, 5.1, 7.6 L/(s·m^2))
3. Obstructions placed across width of plenum (Figure 4)	7-inch plenum: 4-inch (100-mm) and 5.5-inch (140-mm) obstruction at 21 feet (6.4 m) 3-inch plenum: 1 and 2 two-inch(50-mm) obstructions at 21 feet (6.4 m) and 41 feet (12.5 m)
4. Flow resistance of floor grills	Low resistance (open dampers) High resistance (closed-down dampers)
5. Total number of floor grills	16, 32
6. Open panels (panels removed)	Two panels removed near fan inlet in raised floor. Two panels removed at far end of plenum (Figure 4)
7. Change in direction of air flow at fan inlet	Full-height underfloor barriers in front of fan inlets (Figure 4)

4.1 INTERPRETATION OF FLOW HOOD MEASUREMENTS

Inherent inaccuracies of the flow hood for measuring the rather low flow rates (50-150 cfm [24-71 L/s]) at each floor grill required the individual readings to be interpreted as an air flow balancer would, namely to compare individual readings to determine the relative air flow distribution across the test area, as opposed to taking each reading as an absolute air flow result. Flow hood accuracy became a significant issue during the early stages of this experiment as attempts were made to identify and seal all leaks from the plenum (e.g., cracks around the perimeter, holes in the floor panels, etc.) [16]. In a worst-case scenario (highest flow rate in the smallest (2-inch [50-mm]) plenum, producing the highest plenum static pressures), the total air flow leaving the floor grills was 81% of the measured air supply entering the plenum. Considering that flow hood errors of greater that 10% are common, the 19% difference was a reasonable result. In actual raised floor installations, air leakage through cracks between individual panels (smoke visualization indicated this as the most likely source of air leakage) would be significantly reduced by the fact that floor panels would be tighter fitting and covered with carpet tiles (the access floor in the test facility was rather uneven in places and had no carpet on it). In addition, leakage may not be a serious concern in an occupied building because the leakage air will tend to be distributed fairly uniformly across the whole floor area being served by the plenum and will still reach the intended building zone. Finally, plenum operating pressures are always low (0.1 in. H_20 [25 Pa] or less), further reducing the potential for high uncontrolled leakage, except through large openings. For the above reasons, all flow hood measurement results are presented as a fraction of uniform delivered air flow as a primary way to evaluate air flow distribution across the full test area.

5 RESULTS

Experimental results from the underfloor air supply plenum test facility are presented below. Floor grills were initially installed with their dampers largely open (low resistance), resulting in lower than normal plenum static pressures. It was decided to close down the dampers enough (high resistance) to produce an average plenum pressure at the highest air flow rate (1.5 cfm/ft^2 [7.6 L/(s·m^2)]) that was representative of typical operating pressures (0.07-0.08 in. H_20 [17-20 Pa]) for pressurized underfloor air supply plenums using commercially available floor diffusers. Unless otherwise noted, all results presented below are for the grills in the more representative, higher resistance configuration.

5.1 EFFECT OF PLENUM HEIGHT AND SUPPLY VOLUME

Figures 8, 9, and 10 compare the air flow performance for the 7-inch, 3-inch, and 2-inch plenums at nominal supply rates of 1.5 cfm/ft^2, 1.0 cfm/ft^2, and 0.5 cfm/ft^2, respectively. These results are for open plenums (no obstructions) with 32 evenly-spaced floor grills, as shown in Figure 4. In these and subsequent figures, the "distance from fan inlet" represents the distance of each row of outlets (4 grills per row) from the one 40-foot edge of the test area where the fan inlets were located (i.e., 5 ft (1.5 m), 15 ft (4.6 m), 25 ft (7.6 m), etc.). Air flow data are presented in terms of row averages and represent the ratio of measured air flow delivered from each row to the amount of air flow that would be delivered if it were uniformly distributed across the plenum. In other words, a perfectly uniform distribution of air delivery through all floor grills would yield a "delivered air flow ratio" of 100% for each row.

The air flow results of Figure 8 show a very uniform flow distribution for the 7-inch plenum. Although the data shown in Figure 8 are for low-resistance grills, the uniformity of air flow distribution would be expected to be no worse for high-resistance grills. For all flow rates, all row averages varied by less than 10% from a uniform distribution, well within the expected accuracy of the flow hood measurements. The trend for the lower height plenums (Figures 9 and 10) is for more air to be delivered through grills in the first three rows, and less in the rows furthest away from the supply fan. This is particularly true for the higher air supply volume (1.5 cfm/ft^2) for which maximum variations from uniform row averages are 17% for the 3-inch plenum and 27% for the 2-inch plenum. These correspond to end-to-end percent differences of approximately 30% and 40%, respectively. For the 3-inch plenum (Figure 9), air flow performance improved at lower flow rates, as all row averages except one were within 10% of uniformity for 0.5 cfm/ft^2 and 1.0 cfm/ft^2. In Figure 10, the 2-inch plenum is seen to produce comparable variations in delivered air flow ratio for all three air flow rates, indicating that at this reduced height, the plenum surfaces are definitely creating resistance to the plenum air flow. Some of the observed fluctuations in the data may be due to variations in flow resistance of individual floor grills, as the dampers were manually adjusted in an approximate manner to achieve the high resistance grill performance (this is corroborated by the very uniform pressure profiles discussed below). The general conclusion from these air flow figures is that for 7-inch and 3-inch plenum heights, air flow delivery performs with greater uniformity with increasing plenum heights and lower air flow rates. Two-inch plenum heights, on the other hand, do not produce uniform distributions for any of the air flow rates tested.

FIGURE 8 Air flow ratio comparison for three supply volumes (7-inch plenum, low-resistance grills)

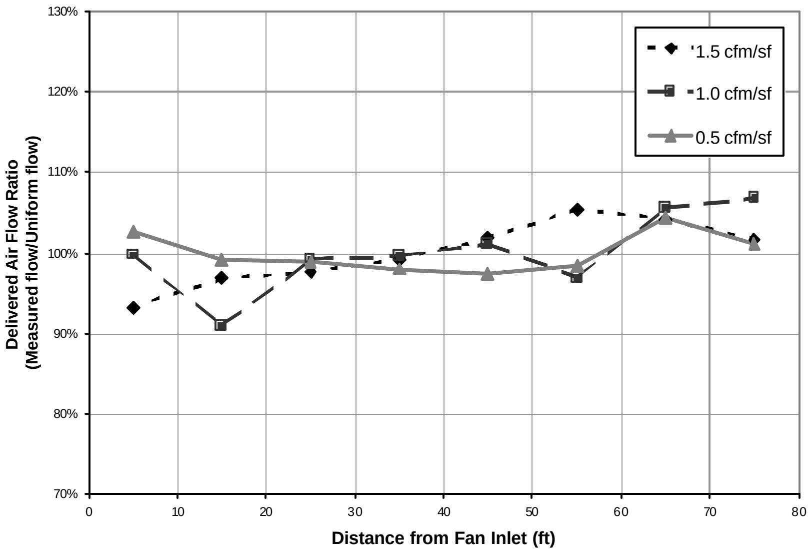


FIGURE 9 Air flow ratio comparison for three supply volumes (3-inch plenum)

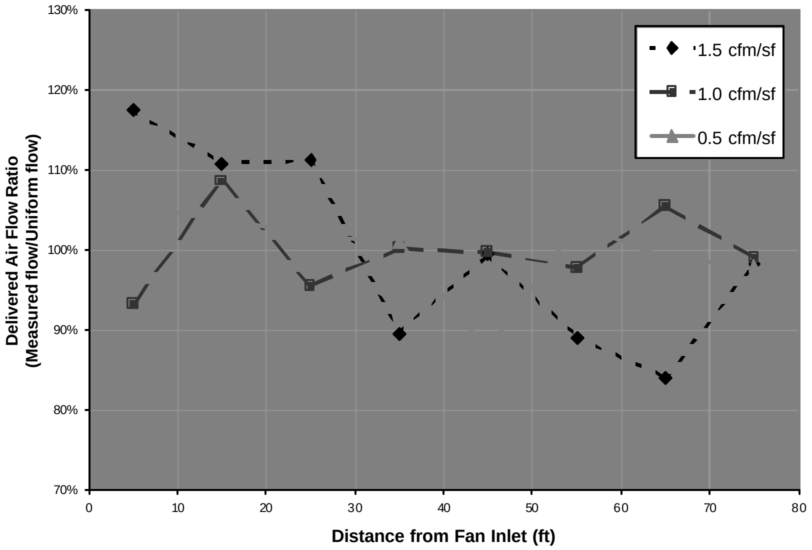
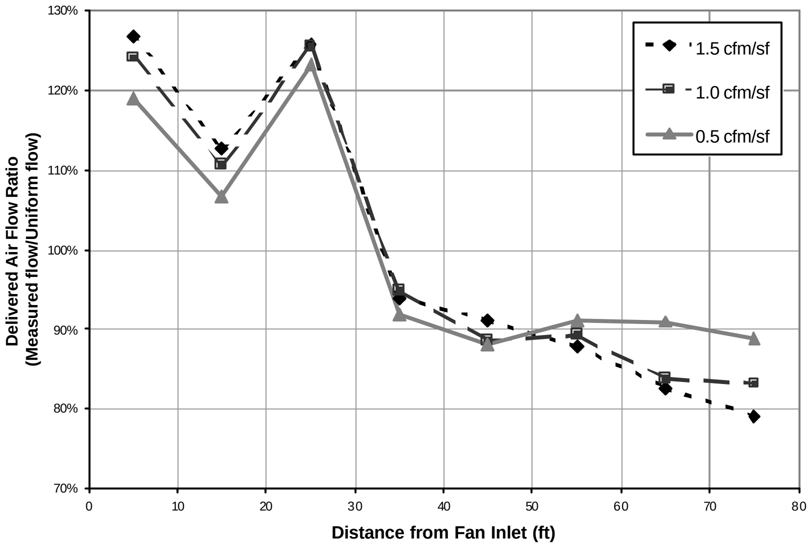


FIGURE 10 Air flow ratio comparison for three supply volumes (2-inch plenum)



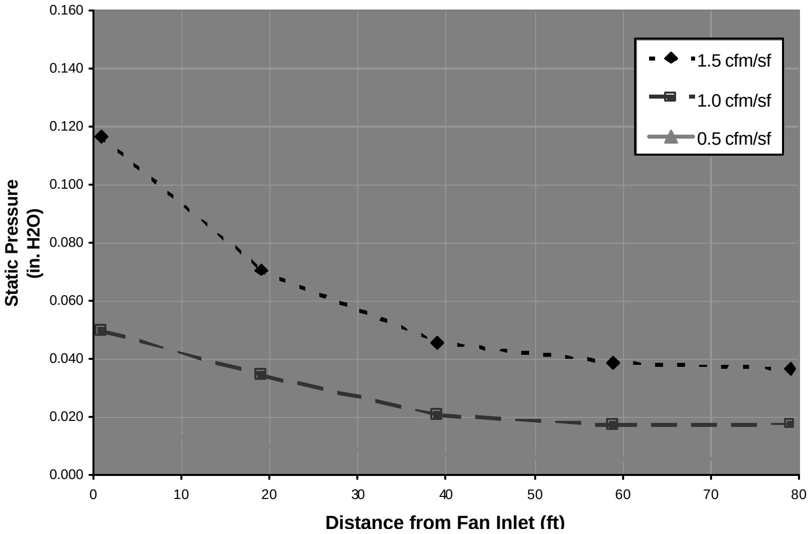


FIGURE 11 Plenum static pressure comparison for three supply volumes (2-inch plenum)

5.2 PLENUM PRESSURES

Pressure measurements in the plenum, in general, support the above described air flow data. Static pressures across the full length of the 7-inch plenum at 1.5 cfm/ft^2 were very uniform and averaged 0.08 in. H_20 (20 Pa). This pressure is in fact representative of typical operating pressures for pressurized underfloor air supply plenums using commercially available floor diffusers. Figure 11 presents measured static pressure distributions for the extreme case of the 2-inch (50-mm) plenum. Referring to Figure 4, each data point represents the row average of the five rows of measurement locations. At 1.5 cfm/ft^2, the static pressure at the near end of the plenum by the fan inlets (0.12 in. H_20 [30 Pa]) was three times greater than the pressure at the far end of the plenum (0.04 in. H_20 [10 Pa]). This variation in pressure corresponds to an expected reduction in delivered air flow from one end of the plenum to the other of about 40%, which is very similar to the results shown in Figure 10. The variations in flow and pressure are also comparable in magnitude to those observed by Hanzawa and Higuchi (1996) for a plenum of similar floor area, but with a smaller height (1.3 inches [33 mm]) and flow rate (0.7 cfm/ft^2 [3.5 L/(s·m^2)]). It should be noted that the air flow data for the 2-inch plenum at 25 ft (7.6 m) appear to be anomalous and inconsistent with the smooth pressure distribution for this case, suggesting that the floor grill adjustments for this row were different from those for the other rows.

5.3 EFFECT OF OBSTRUCTIONS

The effect of obstructions placed across the entire 40-foot (12-meter) width of the plenum (see Figure 4) was also investigated. Figure 12 compares air flow ratios at the highest supply volume for the three different obstruction configurations tested in the 7-inch plenum: no obstruction, one 4-inch obstruction (3 inches of clear space), and one 5.5-inch obstruction (1.5 inches of clear space) at 21 feet from the fan inlet. These tests in the 7-inch plenum were done with low resistance floor grills. If anything, these results could be considered to be slightly conservative in comparison to higher resistance floor grills, which would tend to even out variations in air flow through individual floor grills. Figure 12 clearly demonstrates that an obstruction with only 1.5 inches of clear space for a 7-inch plenum has little effect on the uniform air flow distribution across the length of the plenum. Figure 13 compares air flow ratios at a supply volume of 1.0 cfm/ft^2 for three different extreme cases: 7-inch plenum with one 5.5-inch obstruction, 3-inch plenum with two 2-inch obstructions (1 inch of clear space), and the 2-inch plenum without obstructions. Variations from uniform flow for the 3-inch plenum with obstructions are comparable to the results obtained for the open 2-inch plenum, indicating a significant impact for the 3-inch plenum height.

FIGURE 12 Air flow ratio comparison for different obstructions in 7-inch plenum (1.5 cfm/ft^2)

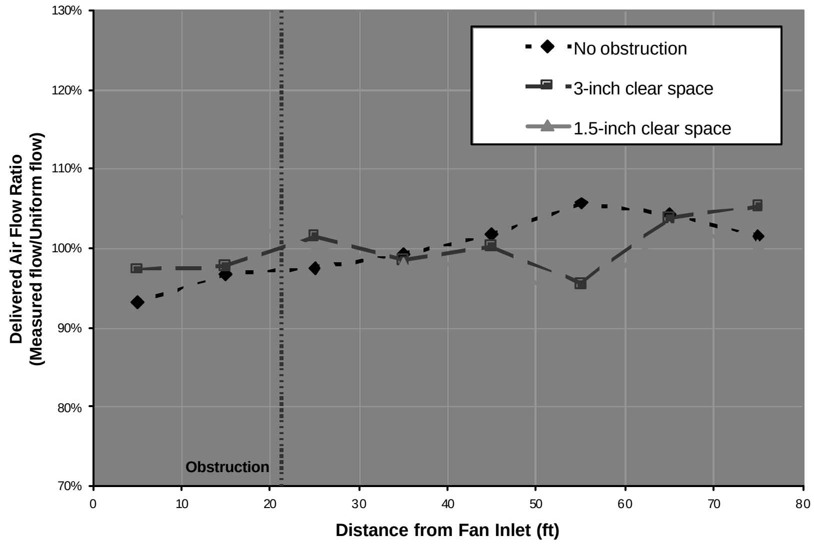
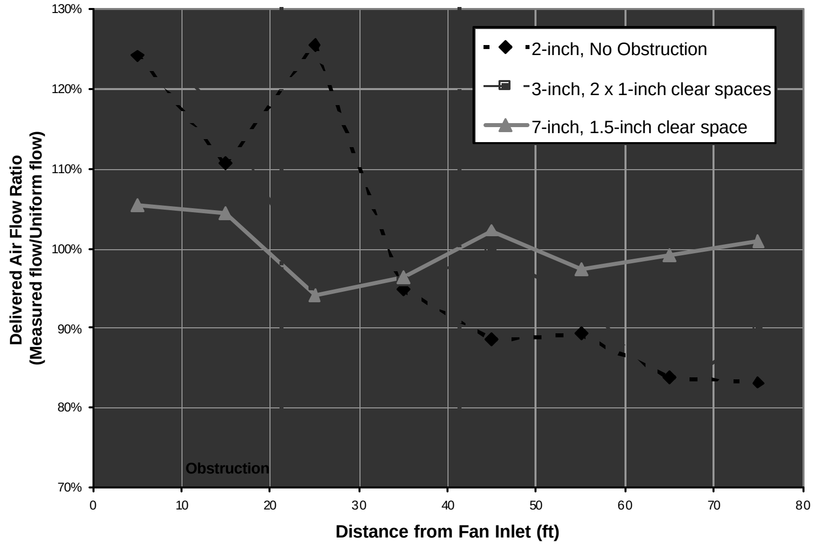


FIGURE 13 Air flow ratio comparison for different plenum and obstruction configurations (1.0 cfm/ft^2)



5.4 EFFECT OF OPEN PANELS

In buildings with raised access floors, floor panels will occasionally be opened to gain access to the underfloor plenum. To investigate the impact of removing panels in a pressurized underfloor air supply plenum on air delivery performance, two floor panels were removed near the fan inlets and then, in a second test, near the edge opposite the fan inlets (see Figure 4). Figure 14 compares the air flow ratios of the system with two open panels at these two different locations against the system with all panels installed (7-inch plenum, 1.5 cfm/ft^2). To estimate the reduction in delivered air flow, air flow ratios for the tests with open panels were normalized using the delivered air flow for the test with no open panels. With two panels open near the fan inlets, the reduction in the amount of air delivered to the outlets was 38%. With two panels open at the opposite end of the floor, the loss was even greater at 51%. As Figure 14 illustrates, roughly half the air was delivered to the outlets when two panels were open, but the distribution continued to be fairly uniform with distance. The results suggest that open panels may be acceptable during temporary periods when access to the underfloor plenum is necessary, such as during the installation or repair of a cable, especially if the open panels are in the same space as the affected outlets. In this case, air is still being delivered to the room uniformly through the floor outlets, but at a lower rate. Overall, the uniformity would be significantly distorted due to the excess volume being delivered through the open floor panels.

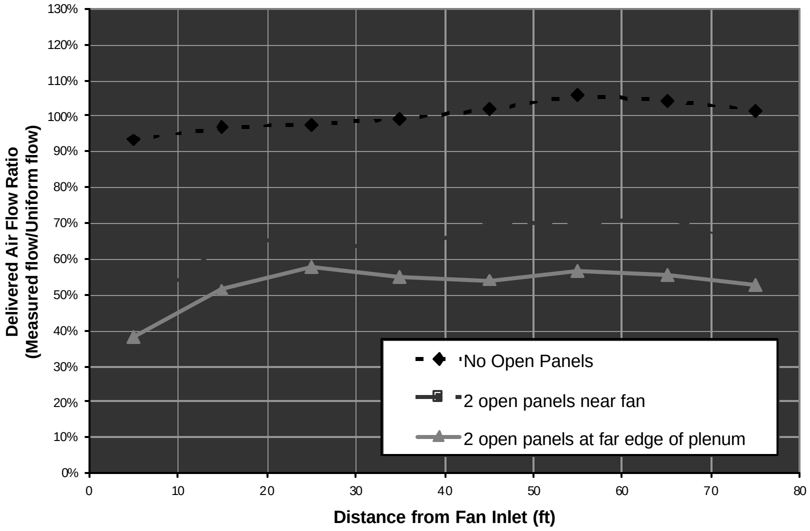


FIGURE 14 Effect of open panels on air flow distribution: 7-inch plenum, 1.5 cfm/ft^2

5.5 EFFECT OF FAN INLET CONDITIONS

The configuration of the fans and inlet ducts in the current experiment resulted in air being supplied with considerable horizontal momentum as it entered the plenum (estimated inlet velocity = 1,200 fpm [6 m/s]). A maximum velocity of 260 fpm (1.3 m/s) was recorded at the centrally located measurement point of the second row (see Figure 4) for the 7-inch plenum at the highest air flow rate. This location, nearly 20 ft (6 m) downstream of the plenum inlet was still affected by the incoming high velocity air. All other velocities for this same test were no greater than 120 fpm (0.6 m/s). Hanzawa and Higuchi (1996) suggest that delivering supply air into a plenum vertically is beneficial as the velocities are immediately decreased by the slab and the static pressure increased, thus resulting in more even distribution. Figures 15 and 16

FIGURE 15 Effect of barriers at fan inlets on air flow ratios: 7-inch plenum, 1.5 cfm/ft^2

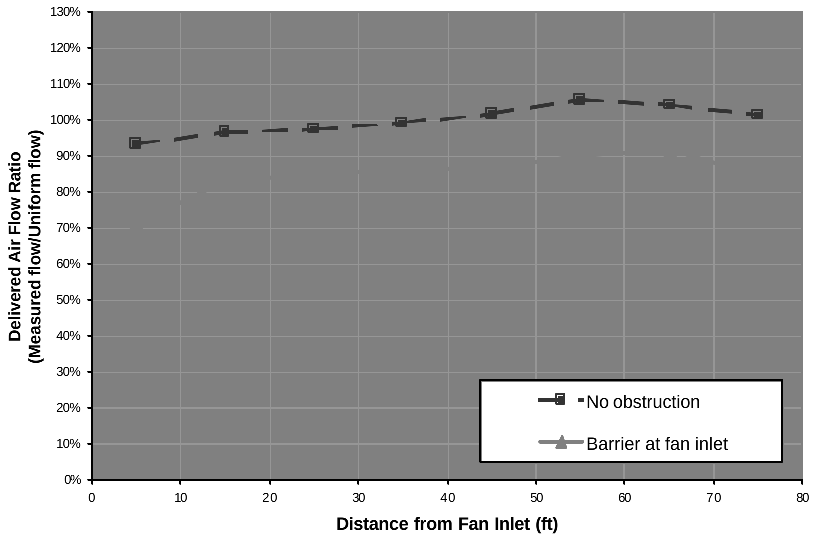
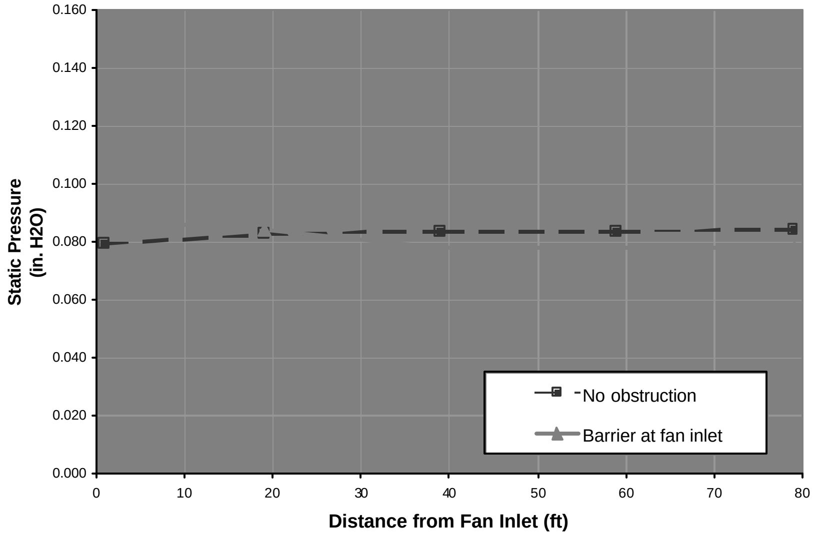


FIGURE 16 Effect of barriers at fan inlets on static pressures: 7-inch plenum, 1.5 cfm/ft^2



show the air flow ratios and plenum pressures, respectively, resulting from installing full height barriers equal in size to the inlet cross-section (4 feet [1.2 m] wide by 7 inches [180 mm] high) in the plenum four feet downstream of the fan inlets (see Figure 4). Results are shown for the open 7-inch plenum at 1.5 cfm/ft^2. Air flow ratios for the test with the barriers were normalized using the delivered air flow for the test with no barriers. The resulting air distribution is no more uniform than the case without the barrier, but it is 14% lower (most likely due to the extra losses imposed by the entry condition). Static pressure in the plenum is very uniform in both cases; only slightly higher near the fan inlets for the case with the barriers and slightly higher at the opposite end for the case with no barriers.

5.6 NUMBER OF OUTLETS

Tests were also conducted in which the number of floor grills was reduced by 50% by removing every other row of outlets, leaving only 16 floor grills in rows 2, 4, 6, and 8. Figures 17 and 18 compare air flow ratios for 32 vs. 16 floor grills at a flow rate of 1.0 cfm/ft^2 for the 3-inch and 2-inch plenums, respectively. Similar air distribution results are obtained for both floor grill arrangements, indicating that there is some flexibility in determining the number of floor outlets for optimal performance, even for the extremely low-height plenums shown here.

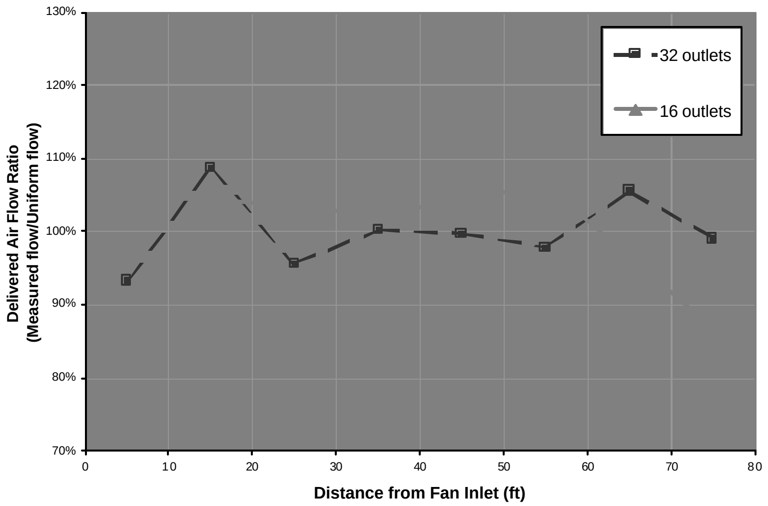
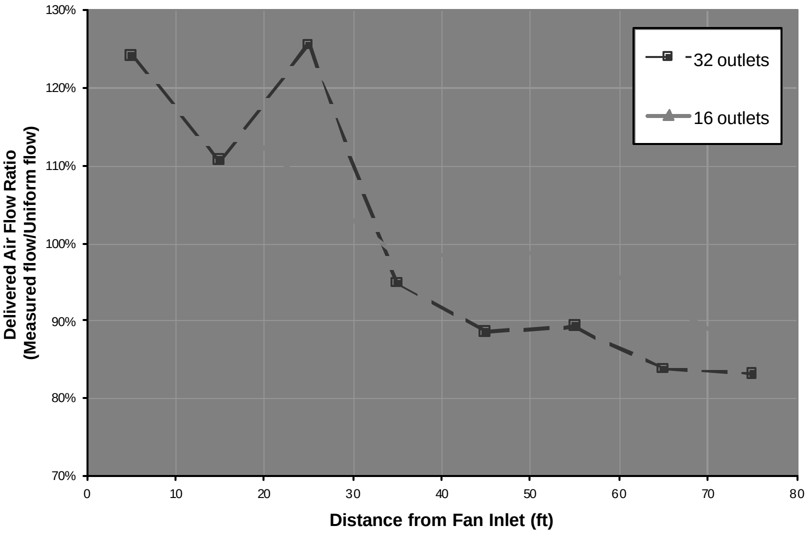


FIGURE 17 Air flow ratio comparison for 32 and 16 floor outlets: 3-inch plenum, 1.0 cfm/ft^2

FIGURE 18 Air flow ratio comparison for 32 and 16 floor outlets: 2-inch plenum, 1.0 cfm/ft^2



6 DISCUSSION AND RECOMMENDATIONS

Full-scale experiments were conducted to investigate the air flow performance of pressurized, low-height, underfloor air supply plenums. The empirical evidence suggests that low-height plenums are feasible and should be considered for wider use in underfloor air distribution systems. The results confirm that air delivery through floor outlets from a pressurized plenum with 7 inches (180 mm) of clear space is very uniform, even at a distance of 80 feet (24 m) from the plenum inlet. This uniformity is preserved over a full range of typical air supply volumes (0.5 to 1.5 cfm/ft^2 [2.5 to 7.6 L/(s·m^2)]), and for the case with an obstruction providing less than 2 inches (50 mm) of clear space. It is interesting to note that in practice, building zones conditioned from a single plenum with a single fan inlet location are rarely this large. As the height of the plenum is reduced (2 to 3 inches [50 to 75 mm] of clear space), the increased resistance to flow within the plenum produces the expected result that plenum pressure and floor outlet air delivery decrease with increasing distance from the fan inlets. However, the maximum average magnitude of these variations from uniform air flow (25-30%) may be small enough to not exclude the use of extremely low-height underfloor plenums under certain conditions. The 3-inch (75-mm) plenum, in fact, demonstrates air flow performance across the 80-foot (24 m) length of the plenum test area at the nominal 1.0 cfm/ft^2 (5.1 L/(s·m^2)) air supply volume (commonly used in building interior zones) that would be considered acceptable based on the criteria defined here (variations of less than 10% from uniformity).

The conclusions and recommendations from this study of pressurized underfloor plenums are presented and discussed briefly below.

1. In practice, the minimum height of an underfloor plenum is often determined by factors other than air flow requirements, including (1) cable management needs, (2) the size of primary air supply ductwork, if the underfloor plenum is being used to deliver ducted air to a separate zone of the building (e.g., perimeter zones), (3) the size of floor diffusers or fan-driven supply units, and (4) the size of other air handling and conditioning equipment. It is recommended that, on average, at least 3 inches (75 mm) of clear space for air flow be provided in addition to the height required for other factors.

2. In a pressurized plenum with at least 7 inches (180 mm) of clear space, acceptable air flow performance over a full range of air flow rates can be achieved through floor outlets located as far as 80 feet (24 m) from the primary air inlet location to the plenum. The uniformity of this air flow distribution will be maintained for floor diffusers having higher or lower flow resistance than that of the outlets used in this study.

3. Solid obstructions, even with only 1.5 inches (38 mm) of clear space above them, may be located in a plenum with at least 7 inches (180 mm) of clear space and have very little impact on the overall air flow performance. In plenums with only 3 inches (75 mm) or less of clear space on average, obstructions cause a more significant degradation to the uniformity of air flow distribution.

4. If one or two floor panels are removed for service or repair work, the amount of air delivered to floor outlets in that same zone may be reduced by up to 50%. However, given that the uniformity of air flow delivered through the floor outlets across the zone is relatively unchanged, this situation may be acceptable on a short-term basis.

5. At the primary air inlet to an underfloor plenum, air may be delivered horizontally or vertically with little impact on the air flow performance in a plenum with at least 7 inches (180 mm) of clear space. For lower height plenums, inlet guide vanes may be used to improve the air flow performance [2].

6. Although increasing the number of outlets in a single plenum zone would be expected to improve the uniformity of air flow distribution, no significant degradation in performance was observed when the number of outlets was reduced by 50% in both 3-inch (75-mm) and 2-inch (50-mm) plenums at a nominal air flow rate of 1.0 cfm/ft^2 (5.1 $\text{L}/(\text{s}\cdot\text{m}^2)$).

7. In practice, safety margins to the results presented here for extremely low-height plenums (2 to 3 inches [50 to 75 mm] of clear space) may be increased by considering the following recommendations.

- Limit the use of extremely low-height plenums to applications requiring no more than 1.0 cfm/ft^2 (5.1 L/(s·m^2)).
- Limit the distance of floor outlets from the nearest primary air inlet duct location to well below 80 feet (24 m), depending on thermal performance.
- Give occupants the ability to control the amount of air flow through individual floor diffusers by adjusting a manual damper, or local fan.
- Operate the plenum in a zero- or slightly negative-pressure mode using fan-driven supply outlets to ensure satisfactory air flow performance.

8. To apply the findings of this study in practice, one should consider the method by which underfloor air distribution systems are controlled. When a constant volume, variable temperature strategy is used, the performance should closely follow the results shown here. However, when a VAV strategy is used, one would expect more uniform air flow performance as load decreases, or, in other words, the most non-uniform air flows would occur only for peak load conditions. Of course, the number of operating hours at peak load depends on the load profiles for the type of zones served.

9. Another important consideration will be the thermal performance, or variations in supply air temperature across the area of the plenum. Depending on conditions at the time, if heat transfer from/to the concrete slab and other surfaces in the plenum results in supply air temperatures that are either too high or too low, the thermal environment of the room may deteriorate, particularly at large distances from the plenum inlet. The next phase of this project will address thermal performance issues (see below).

7 FUTURE WORK

In addition to the air flow performance findings of this report, thermal performance issues will play an important role in the optimal design and operation of underfloor air supply plenums. Future work on this CBE project will investigate the thermal performance of underfloor plenums through a combination of full-scale experiments and CFD (computational fluid dynamics) and other modeling methods. Key issues to be addressed will include the thermal storage in the concrete slab, the heat transfer rate to the underfloor air supply, and air temperature variations across the plenum. Whole-building energy simulations will also be performed to study the energy use implications of using underfloor air distribution.

On the commercial side, more products are needed that support the wider application of underfloor air distribution technology. In particular, low-height underfloor plenums, as discussed in this paper, will require the development of low-profile floor grills, supply modules, and other air distribution equipment.

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