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Supply Fan Energy Use in Pressurized Underfloor Air Distribution Systems

Tom Webster, P.E., Fred Bauman, P.E., and Erik Ring,. P.E.

EXECUTIVE SUMMARY

This preliminary study explores the impact of various design assumptions on the supply fan energy consumption of pressurized underfloor plenum systems as compared to that of traditional overhead constant air volume (CAV) and variable air volume (VAV) systems.

The results of this study indicate that, in terms of optimizing energy efficiency, variable air volume (VAV) control of supply air is the preferred method of cooling perimeter zones of pressurized underfloor air distribution (UFAD) systems just as it is for overhead (OH) systems. Moreover, cooling fan energy consumption for underfloor VAV systems can be significantly less than that for overhead VAV systems. Results show also that constant air volume (CAV) systems can be an effective approach for zones, such as core areas, that have little load variation (assuming oversizing is minimized). For these situations a UFAD-CAV system can offer low installed cost, simplicity, and provide modest energy savings compared to an overhead VAV system.

SOME BASIC CONCEPTS

Fan Energy

Total HVAC energy for any system is composed of two major components:

- Fan, or ventilation energy, and
- Central plant energy (i.e., cooling, heating, pumps, and other central plant/system level equipment).

Fan energy in turn consists of two components:

- Terminal unit fan energy – Energy associated with air movement for fan-powered terminal devices such as active floor diffusers, fan-powered variable air volume (VAV) boxes, and air-water devices like fan coil units and water source heat pumps (WSHP).
- Central fan energy – Energy consumed by the supply fans and return/exhaust fans serving multiple zones. The total HVAC energy consumption of underfloor systems, although typically less than comparable overhead systems, depends heavily on architectural and mechanical design parameters.

Underfloor Systems

Underfloor systems can be divided into two basic classes[1]:

- Pressurized (passive) systems
- Zero-pressure (active) systems

Pressurized systems are characterized by air distribution via passive[2] diffusers operated in constant volume or variable volume mode or by variable volume (modulating) floor diffusers. These plenums typically are operated at pressures in the range of 0.05 to 0.1 in. w.c. For passive UFAD systems where the central fans handle the entire supply airflow, fan energy use depends on supply and return/exhaust fan energy consumption.

Zero-pressure systems rely on space distribution via active/fan-powered diffusers, are operated at zero or negative plenum pressures, and include a significant amount of mixing between cool supply air and space/return air in the plenum. This latter characteristic results in less total air being handled by the central fans of zero-pressure systems and thus potentially lower central fan energy consumption.

Note that these basic classes of UFAD systems are "idealized" solutions that in practice are applied in individual areas of a building or in combination with each other and/or in combination with standard overhead system components forming "hybrid" solutions[3]. These hybrid systems consist of combinations of passive floor diffuser products, traditional terminal devices, and custom designed equipment. Solutions run the gamut from worst case scenarios where a ducted overhead system is simply placed in the underfloor plenum, to combinations of fan-powered and passive floor diffusers with ducted and unducted terminal devices such as VAV boxes and fan coil units. One fairly typical solution is to use a passive diffuser UFAD-CAV system in the core and fan-powered VAV reheat boxes or fan coil terminals in the perimeter.

Pressurized UFAD systems typically are based on two basic types of all-air systems:

- Constant air volume (CAV), variable temperature
- Variable air volume (VAV), constant temperature

Constant volume underfloor systems (UFAD-CAV) rely on variation of supply air temperature to control space temperature. While changes in local airflow can result from occupant changes of diffuser settings, the overall the supply volume is held constant. Ideally, pressurized underfloor *Variable air volume* (UFAD-VAV) systems would be controlled by automatically varying the volume from a set of passive floor diffusers in response to zone temperature. This requires some way to control plenum pressure (and thus AHU capacity) based on zone temperature.

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[1] Underfloor implementations of classical overhead systems might be considered a third class, but these are not of interest to this study.

[2] Non fan-powered, fixed (non-varying/modulating)

[3] A thorough review of the many solutions being tried is beyond the scope of this paper but will be the subject of ongoing CBE work in this area.

BACKGROUND

There has been a significant amount of development and analysis of UFAD technology, its application and benefits, but relatively little research has been conducted on the energy use of these systems. Since fan energy can consume a significant fraction of overall HVAC system energy (up to 40% in typical overhead systems), it is important to look for ways to reduce this component as much as possible. One way to evaluate fan energy use in UFAD systems is to compare its use with that of traditional overhead systems. Our objective for this study is to assess the impact of cooling fan energy consumption in UFAD systems by comparing to overhead system consumption. This information, although it needs to be augmented by more thorough energy simulations work, provides designers and energy analysts some insight into how their system design choices are likely to impact this important energy component.

METHODOLOGY

In this study we explored the impact of various design assumptions on the supply fan cooling energy consumption for pressurized UFAD systems by comparing to that of traditional overhead CAV (OH-CAV) and VAV (OH-VAV) systems.

Cooling fan energy consumption for pressurized UFAD systems was characterized by determining fan energy requirements versus cooling load factor for the following three comparisons:

1. Comparison #1: UFAD-CAV to OH-CAV

2. Comparison #2: UFAD-CAV to OH-VAV

3. Comparison #3: UFAD-VAV to OH-VAV

To perform these comparisons, idealized fan throttling curves were created for typical overhead VAV and pressurized UFAD systems. Due to reduced distribution ductwork for UFAD systems, it was assumed that central fan static pressure requirements could be reduced by 25% compared to overhead systems. In addition, the analysis considered the combined impact of increased supply air temperature and heat gain stratification that are key characteristics of UFAD systems.

The focus of this study was on central fan energy consumption for *pressurized* UFAD systems where the entire supply air volume is handled by the central AHU. We explored central fan energy consumption for “idealized” cases where only passive floor diffusers are used. Hybrid systems that are more often used in practice generally would consume *more* energy than these idealized cases, due to the added energy of fan-powered terminal devices or ducted supply air.

RESULTS

For CAV systems, the results for Comparison #1 above indicate moderate fan energy savings can be achieved for UFAD-CAV systems compared to OH-CAV systems. These savings are derived from reduced static pressure requirements for UFAD-CAV systems.

Results for Comparison #2 (UFAD-CAV to OH-VAV) shown in Figure 1 indicate that UFAD systems using a CAV strategy will consume more fan energy than OH-VAV systems for most load conditions. However, at load conditions above about 80% there are slight savings for UFAD-CAV systems. This indicates that for systems with low load variation and minimal oversizing, a UFAD-CAV solution would be acceptable.

Figure 1. Fan Energy Use for UFAD-CAV vs. OH-VAV systems

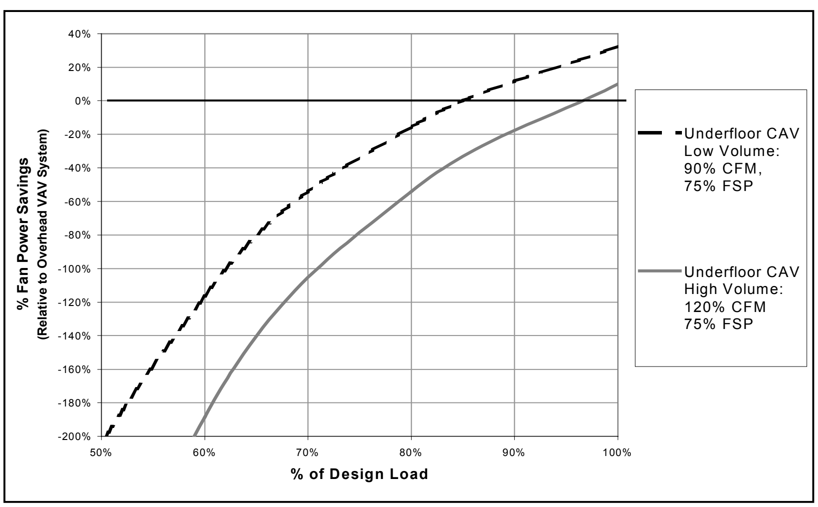
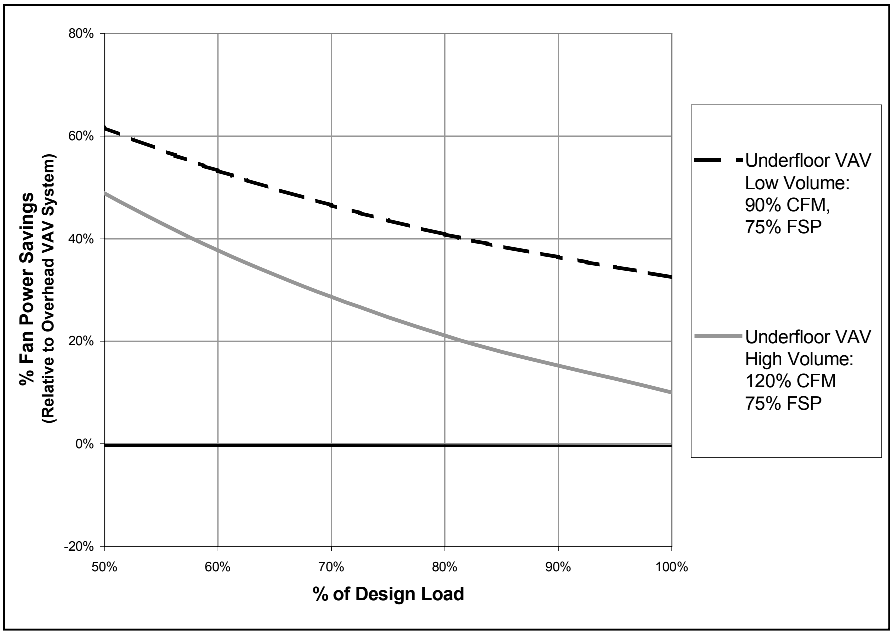


Figure 2. Fan Energy Use for UFAD-VAV vs. OH-VAV systems



The results for Comparison #3 (UFAD-VAV to OH-VAV) shown in Figure 2 indicates that a VAV strategy implemented in UFAD systems (without pressure consuming terminal devices) can result in significant central fan energy savings compared to typical OH-VAV systems for all operating conditions.

DESIGN ISSUES

While these results indicate a clear preference for VAV solutions for passive UFAD systems to minimize central fan energy for cooling, there are many practical system design and cost reasons for choosing a particular solution. The results from this study represent the potential for "pure" pressurized UFAD systems. The crux of the designer's problem, however, is how to satisfy diverse zone requirements (i.e., core, perimeter, conference rooms, etc.) with a well-integrated system. These solutions are rarely "pure," as attested to by the wide variety of "hybrid" UFAD system designs being implemented. Any given system design solution depends heavily on numerous design constraints. The following list provides a brief overview of some of the design challenges:

- Perimeter zones require significant compromises due to load variation, number of control zones, peak load levels, and the need to provide both heating and cooling with minimal overlap. Designers tend to choose some form of VAV system using standard overhead components either by themselves or in conjunction with UFAD diffusers for these zones. Fan coils also have been used for these zones but they tend to result in more maintenance and energy consumption than passive approaches.

- Integration of systems becomes more complex if VAV is used in the perimeter but is not used in the core of an open plan space. In this case underfloor zone barriers are called for to isolate the plenum spaces. Barriers may be required for CAV systems as well. For example, if exposure control is used in the perimeter, it will need to be isolated from the core zones. [1] Integration of core, perimeter, and special zone systems can result in different solutions for different types of spaces. Integration is complicated by the fact that there is limited availability of products that provide for a complete solution for all types of zones.
- Some designers contend that perimeter zones with large loads cannot be served effectively with passive floor diffusers using 63ºF supply air even if the zone is open plan and therefore does not require control of small zones. [2] Passive floor diffusers tend to handle small volumes and therefore their use in heavily loaded zones may require a large number of closely spaced diffusers that may have an impact on space layout as well as comfort due to excessive airflow in the zone. Certainly there is a limit to how much load can be accommodated with 63°F air, but ultimately it is the degree of stratification achieved that will determine the airflow requirements as indicated by Figure A2 in Appendix A. This situation is impacted also by the lack of well-established load analysis methodologies, which leaves designers without a consistent and accurate way to predict required airflow rates and temperatures in occupied portions of the space.
- Anecdotal accounts from designers indicate that floor diffuser performance has a significant impact on the amount of stratification achieved. In general there is a dearth of information that verifies the stratification performance of various diffusers under different load conditions. Diffuser performance should be carefully analyzed when systems are designed.
- CAV solutions may be preferable for core zones where load variation is small (and oversizing is minimized) since VAV solutions add complexity and cost that may be unnecessary. UFAD-CAV systems may also be appropriate for large open plan perimeter spaces with moderate loads that can be controlled on an exposure basis.
- Automatic control of passive diffuser systems is not straightforward, especially when integrated with solutions for other types of zones.

These considerations indicate that better alternatives need to be developed. Two promising approaches currently being tried are:

1) Passive VAV diffusers [3], and

2) Hybrid systems using both active and passive diffusers. [4]

Hybrid solutions that combine passive floor diffusers and active devices, such as Tate's TAM, TROX fan terminal units or other terminal equipment, allow a highly loaded perimeter zone to be "base loaded" by passive diffusers, which are then augmented by active devices to cover load variations and zoning requirements. From the standpoint of total fan energy (i.e., central plus terminal fan energy), these may not be ideal but may be more practical where a more ideal solution is not possible or is too costly.

These are just a few of the considerations that designers must juggle. When all architectural and mechanical constraints and the impact of such "intangibles" such as churn are included, the final solution is most likely going to entail a number of compromises that may override a more ideal solution.

FURTHER RESEARCH RECOMMENDATIONS

In this study we have presented simple idealized comparisons for pressurized UFADs only. We currently plan to extend this work by conducting additional research in one or more of the following areas:

- Active systems – Since these systems are a viable alternative to be considered, it is important to understand the combined terminal and central fan power requirements for these systems.
- Hybrid systems – Most practical designs to date are hybrid solutions with combined passive, active, and/or traditional HVAC elements. A review of a number of these designs would frame the range of design options used in practice and is a necessary preliminary step to an analysis of fan power requirements for various practical system alternatives.
- Whole-building energy analysis – Fan power is only one component of total HVAC energy consumption. Fan power needs to be compared to overall energy use on an annual basis in a variety of climates and for various building architectural design alternatives to obtain a true perspective on the implications of various UFAD system design options. Unfortunately, there are no existing simulation tools that adequately characterize underfloor UFAD systems and the wide variations of system options being used. We will continue to explore the possibility of developing such a capability to facilitate conducting parametric studies.
- Floor diffuser performance – Floor diffusers appear to have a significant impact on stratification potential. Research needs to be done to better understand diffuser interaction with plume driven convective loads and to identify the variables that impact stratification performance.

APPENDIX A – RESEARCH DETAILS

METHODOLOGY AND ASSUMPTIONS

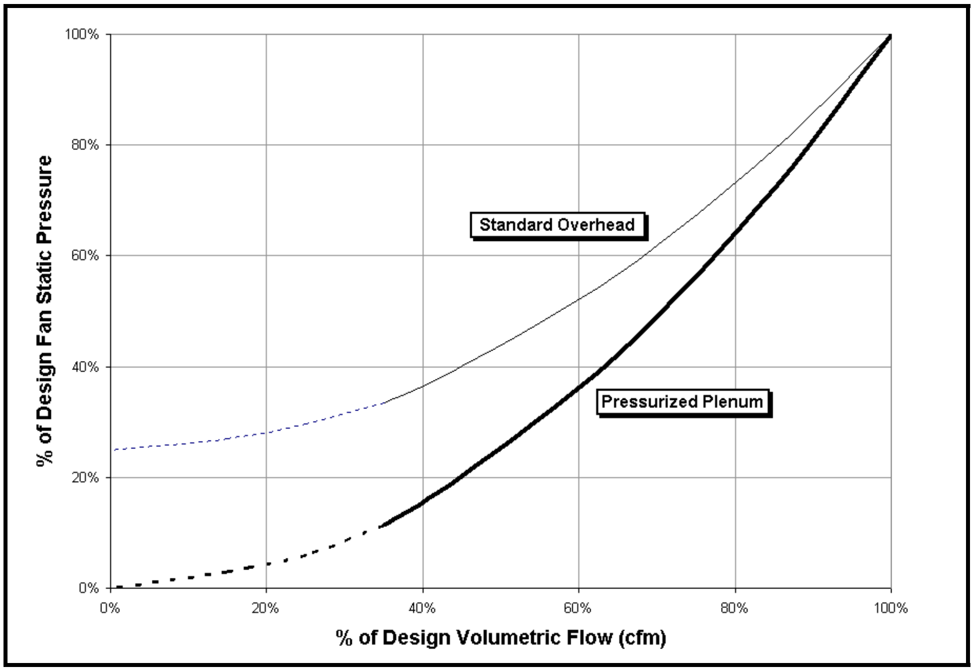
Procedure

To ascertain the impact of design choices on fan energy in pressurized UFAD systems, we compared fan energy use for cooling between UFAD systems (both CAV and VAV) and "standard" overhead systems as outlined below. Our simplified analysis method allows us to identify general, relative differences in fan energy requirements without conducting simulations.

The following procedure was used to compare the energy use between various cases:

- A standard throttling curve was assumed (Figure A1) for OH-VAV supply fans with a static pressure setpoint, or (theoretical) static pressure shutoff at 25% of design fan static pressure (FSP). [5]
- A different throttling curve (Figure A1) with a 0% static pressure cutoff was assumed for UFAD supply fans. This throttling curve is similar to the curve for a return fan in a standard VAV system (i.e., assuming negligible UFAD pressure, there is no "shutoff" static pressure for these systems).
- The power ratio (subject case part load fan power divided by full load power for the overhead case) curve was computed for each of four pressurized UFAD cases; each case represents a specific design assumption. Note that fan power is proportional to FSP multiplied by volumetric flow for any given load condition.
- Using the resulting fan power ratio curves, savings can be determined by comparing the power ratio for the various underfloor cases to the overhead system power ratio at the equivalent load factor.

Figure A1. FSP vs. Flow for Overhead and Pressurized UFAD VAV Systems



Assumptions

Our analysis is based on the following assumptions:

- Uniform supply airflow and supply air temperature distribution from the UFAD system (i.e., no added supply ductwork or temperature compensation strategies).
- A well-designed (i.e., not over-designed) standard OH-VAV system consisting of pressure independent VAV boxes with variable speed drive (VSD) volume control of the central fans using a standard practice static pressure control feedback loop. We have assumed that static pressure is controlled to 25% of the design fan static pressure or a 4:1 pressure turndown ratio. For example, a fan with a 4” w.c. design static pressure, would have a static pressure control setpoint of about 1” w.c. Fan energy use by standard VAV systems is strongly dependent on this design parameter.

  Note: Fan energy consumption by OH-VAV systems is significantly diminished if *static-pressure reset* control techniques are used. Although this control strategy is not commonly used in practice today, a modern DDC control system could easily accomplish this more optimal control strategy. If static pressure reset was used in the baseline OH-VAV system, fan energy reductions due to throttling differences shown in Figure A1 would be virtually eliminated; only the differences in static pressure requirements due to reduced supply ductwork would contribute to the savings.
- Airfoil type supply air fans in the range of 10,000-20,000 cfm have been assumed for this study. Typical static efficiency for these fans is

in the range of 60-80%. This efficiency changes only slightly over the normal operating range of these fans (assuming they are reasonably sized), and so constant efficiency was assumed for this study. Typically these would serve a 10,000-20,000 ft^2 area that may be divided into a few large UFAD spaces. This study focuses on the supply fans only; a more thorough study would consider the overall system fan energy including return and/or exhaust fans.

- Fan inlet side (coils, filters, dampers etc.) of a UFAD system is assumed to be virtually identical to a standard overhead system [4]. The fan discharge side, however, would be significantly simpler for the UFAD system. Typical design pressure drops for OH-VAV systems are shown in Table A1.

Table A1. Typical Design Pressure Drops

System Element	*% of FSP**	*Typical static range*
Supply side (filters, coils, etc.)	50%	~ 2”
Trunk ductwork	25%	~ 1”
Terminal/Branch ductwork**	25%	~ 1”
Total	100%	~ 4”

* FSP refers to fan static pressure, the catalogue rated pressure rise for a given operating point.

** Assumes VAV boxes and CAV reheat coils and their associated branch ductwork have similar losses.

- We have assumed that static pressure requirements could be reduced 25% due to elimination of terminal and branch ductwork (i.e., it is assumed that no VAV boxes or other pressure consuming terminal devices are connected to the trunk ductwork of the zones served). Static pressure reduction is highly dependent on the specifics of a particular system design. Twenty-five percent reduction may be conservative, others [3] indicate that static pressure can be reduced further thus producing even greater savings. For perimeter systems this represents cases where passive VAV floor diffusers, or a hybrid combination of passive floor diffusers and fan-powered devices (i.e., to overcome added resistance of the terminal device) are used.
- Static pressure in UFAD systems has a negligible effect on fan design pressure compared to other pressure losses.

[4] This may not be strictly true for systems located in humid climates. Although both overhead and UFAD systems require dehumidification, UFAD systems might require additional equipment (e.g., desiccant equipment) for these climates due to the warm delivery temperatures.

- For underfloor systems the design supply air temperature is assumed to be 63°F, since a design temperature much lower than this is likely to cause discomfort even at peak loads.

Cases Analyzed

There is considerable uncertainty (and therefore a perception of risk) in the design community about how to determine zone airflow requirements. Two opposing factors influence the air flow requirements of UFAD systems: increased supply air temperature which increases air volume requirements, and heat gain stratification that results in a greater overall temperature difference and thus tends to reduce airflow requirements. It is the assumption of stratification effect that is the source of the uncertainty. The degree of stratification results from a complex interaction between vertical distribution of heat gains, space and system layout, and diffuser performance. Some designers take credit for this stratification by reducing design zone loads or by increasing design temperature difference.[5] Figure A2 shows the combined impact of greater supply air temperature and increased stratification on design airflow requirements. To show the impact of these considerations, we selected cases for 90%, 100%, and 120% of overhead system design airflow for our analysis. Table A2 shows a summary of the cases analyzed. These underfloor cases cover a broad range of UFAD system design scenarios that range from Underfloor case 1 where no credit is taken for reduced pressure or increased stratification, to Underfloor case 4 where 25% FSP reduction and 10°F stratification are assumed.

[5] For UFAD systems the temperature in the occupied portion of the space depends on the heat gain to this region, which is typically lower for OH systems thus further lowering airflow requirements. This effect is the subject of ongoing CBE research.

Figure A2. Airflow Factor[6]

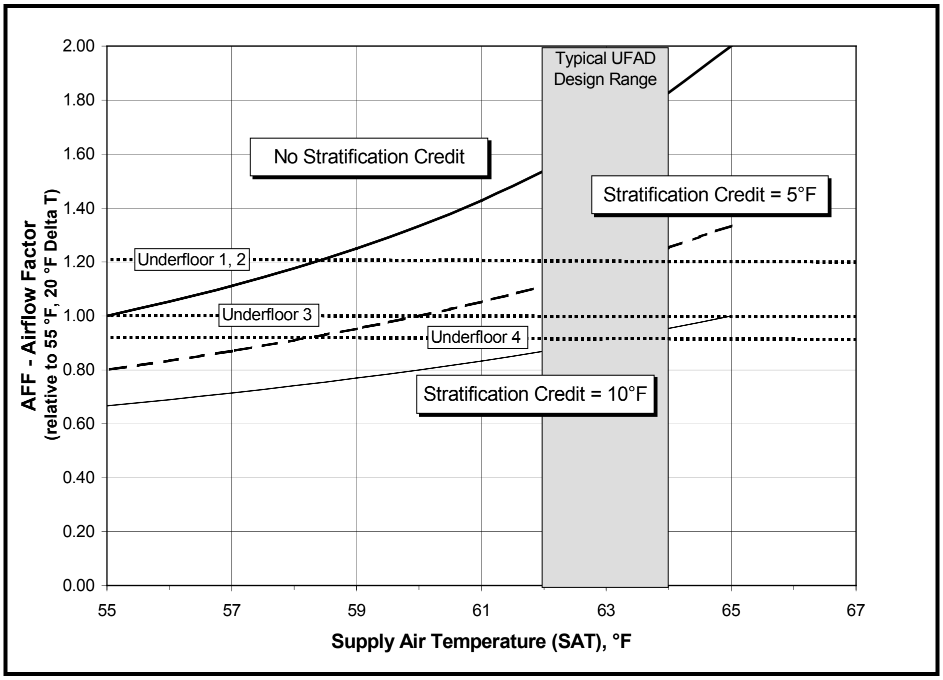


Table A2. Cases Analyzed

Case	*% of overhead design CFM*	*% of overhead design FSP*
Overhead	100	100
Underfloor 1	120	100
Underfloor 2	120	75
Underfloor 3	100	75
Underfloor 4	90	75

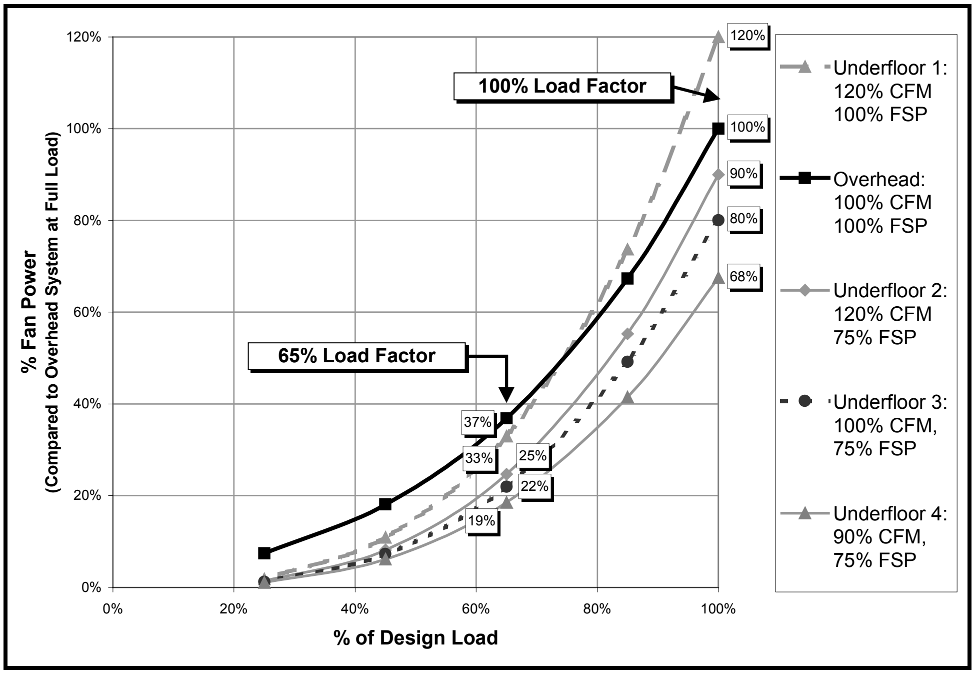
RESULTS

Fan Power Ratios vs. Load Factor

Figure A3 shows a plot of fan power ratios vs. load factor for the overhead case and the four underfloor design cases. Note that the power ratios for each curve is computed relative to full load fan power of the overhead system (i.e., fan power at a given load condition divided by full load fan power for the overhead system). Note also that the abscissa is the percentage of design load (the same for all cases).

[6] Stratification Credit refers to the magnitude of the return air rise above a nominal 75°F room temperature.

Figure A3. Fan Power Ratio vs. Load Factor for Overhead and Underfloor Design Cases



Average Annual Load

Figure A3 can be used in two ways. For any given load factor the fan power ratio can be compared between the overhead case and any other case of interest. For annual energy estimates, an average annual load factor can be used. Typical average annual load factors are shown in Table A3. [2, 5]

For example, Figure A3 shows the fan power ratios for the case of a 65% load factor, typical for a fan that serves both core and perimeter spaces. If the values for the underfloor cases are compared to that of the OH-VAV system, an assessment of the savings between a UFAD-VAV and an OH-VAV system can be calculated as shown in Table A4.

Table A3. Typical Average Annual Load Factors

Load types	*Average annual load factor, % Design load*
Low load variation (e.g., Core zone)	80-100%
Wide load variation (e.g., Perimeter zones)	40-70%
Combined (e.g., core plus perimeter)	65%

Table A4. Example Comparison, UFAD-VAV vs. OH-VAV

Case	*Fan Power Ratio*	*Ratio of UFAD-VAV Fan Power to OH-VAV Fan power.*
Underfloor 1	33%	89%
Underfloor 2	25%	67%
Underfloor 3	22%	59%
Underfloor 4	19%	51%

Savings Assessment

UFAD-CAV vs. OH-CAV

A comparison between UFAD-CAV and OH-CAV systems can be readily made from Figure A3 at the intersection of the power ratio curves with the 100% load axis, since CAV systems do not throttle airflow. Figure A3 indicates that compared to an OH-CAV system, central fan energy savings for Underfloor cases 1, 2, 3, and 4 are –20%, +10%, +20%, and +32%, respectively. These results indicate that reductions in fan pressure requirements and total airflow (using load reduction credit for heat gain stratification as in the Underfloor case 4) can result in significant central fan energy savings.

UFAD-CAV vs. OH-VAV

Since many pressurized UFAD systems are designed as CAV systems, it is instructive to compare UFAD-CAV systems to standard overhead VAV systems. From Figure 1, in the body of the report, which compares fan energy savings for two CAV underfloor cases to the VAV overhead case, it is obvious that UFAD designs that use CAV result in considerably more fan energy use than OH-VAV systems. The only exception to this is for load factors above about 85% for the low-volume and low-pressure underfloor condition (Underfloor case 4). Although, energy savings inherent with underfloor HVAC systems typically would yield positive total HVAC energy savings, this result indicates that in general VAV alternatives to CAV should be considered for zones that operate with load factors below about 80% for significant periods of the year.

UFAD-VAV vs. OH-VAV

Figure A3 indicates that there are no central fan energy savings for UFAD systems using a VAV strategy *without* reduced static pressure, for load factors above about 75% (Underfloor case 1). On the other hand, Figure 2, in the body of the report, which compares fan energy savings for two VAV underfloor cases to the overhead VAV case, indicates that there are significant savings for all load conditions when static pressure is reduced (Underfloor cases 2, 3, and 4). This is especially true when design airflow is reduced by taking credit for heat gain stratification (Underfloor case 4).

APPENDIX B – REFERENCES AND BIBLIOGRAPHY

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