AIR DISTRIBUTION FOR COMFORT AND IAQ

Heating Piping and Air Conditioning

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EXCELLENCE IN AIR DISTRIBUTION

Modern environmentally controlled spaces consume significant amounts of energy in maintaining a stable environment within the structure. The demands for heating and cooling vary greatly over time, and different strategies are employed to respond to these varying loads. Ventilation requirements must also be met by the HVAC system. This conditioned and ventilated air must be effectively delivered to the building occupants.

There are two principal design conditions in HVAC systems. Perimeter zone loads vary over a broad range from heating to cooling, and are affected by both exterior and interior factors. In interior zones the heat generated by lights, occupants, and office machinery provides a continuous cooling demand.

The proper selection of diffusers is necessary to ensure that both occupant comfort and adequate ventilation mixing are provided. As the choice of diffusers is based on both engineering and architectural concerns, both the engineer and the architect need to have a say in the final selection. In addition, the ideal selection is dependent on the type and operation of the air supply to the diffuser. While there are many ways of supplying conditioned air to an office space including displacement ventilation, underfloor vertical air distribution and task cooling, this article will deal with the predominant method, the ceiling supply air diffuser.

ASHRAE continues to sponsor research into the performance of air distribution elements, and much has been written on the subject in both technical papers and magazine articles. At the same time, ASHRAE Standards for Indoor Air Quality (62-1989) and Comfort (55-1993) state requirements for the resulting ventilation mixing, air temperatures and airspeeds, and even turbulence intensity (the rate of change of the local air speed) in the zone. Awareness of Indoor Air Quality issues and concern over occupant complaints has increased the visibility of proper diffuser selection, location, and design. At the same time, complaints of 'stuffiness' are finally being diagnosed as temperature, not Indoor Air Quality complaints.

The ASHRAE handbook provides recommendations for diffuser selection, which have been included in at least one lawsuit as being the 'acceptable standard of care'. All available research indicates that when air distribution is provided from the ceiling, a thoroughly mixed condition, throughout the space, is the desired result. Furthermore, the research has proven that with properly selected ceiling diffusers, excellent air distribution and ventilation mixing can be achieved with many types of diffusers, and in many types of spaces, including the open landscape office.

The key element here is the term 'properly selected'. Diffuser selection ranges from the selection of a 'hole cover' (or 'architectural duct termination') to a detailed analysis of the diffuser air supply pattern in each zone. A zone-by-zone analysis is almost always prohibitive in terms of design time, and probably not necessary for most spaces. Interior open office spaces, which are typically in cooling mode year round, can usually be characterized in a general way, and excellent diffuser selections made for these locations. Perimeter zones are more complicated, with both thermal and aerodynamic concerns to be considered, but again, these can often be characterized in a general way for the building design, and excellent air distribution can be achieved. When there are problems, it is our experience that there was little (or no) actual air distribution design, loads are considerably different than planned, or products were installed which did not meet the designer's specifications.

The ASHRAE Handbook of Fundamentals, Chapter 31, provides two basic rules for overhead heating and cooling:

1.) In cooling mode, diffuser selection should be based the ratio of the diffuser's throw to the length of the zone/area being supplied, at all design air flow rates, to achieve an acceptable Air Diffusion Performance Index (ADPI).

2.) In heating mode, the diffuser to room temperature difference (delta-t) should not exceed 15^{o} F, to avoid excessive temperature stratification. ASHRAE Standard 55-1993 defines the level of acceptable vertical temperature gradation.

ADPI statistically relates the space conditions of temperature and air speed to occupants' thermal comfort. This is similar to the way NC relates local conditions of sound to occupants' noise level comfort. High ADPI values are desirable as they represent a high comfort level. Acceptable ADPI conditions are shown in the Fundamentals Handbook for velocities less than 70 fpm and velocity-temperature combinations that will provide better than the 80% occupant acceptance.

In analyzing a test of air temperatures and air speeds in a loaded space, the temperature and velocity at each measured point are used to calculate an effective draft temperature. A draft temperature of 0 is essentially thermally neutral. Negative draft temperature equates to a sensation of cool, whereas positive values represent a predicted feeling of warmth. The percent of points, measured in the occupied zone, having a calculated draft temperature between -3 and +2, where the air speed is < 70 fpm, results in the ADPI.

The ADPI curves in the ASHRAE *Handbook of Fundamentals* (Chapter 31) summarize some of the tests that established ADPI and the relationships from which this selection procedure originates. The curves show relative comfort for:

- Four different outlet types
- Catalog throws and space characteristics
- Loading (1 cfm/SqFt with a 20° F differential is a load of about 20 Btuh/SqFt)
- Flow rate (variable volume)

L is the space characteristic length in feet. This is usually the distance from the outlet to the wall or mid-plane between outlets. This can also be considered the module line when outlets serve equal modules through a space, and all consideration can then be based on the module parameters. (See table 1)

T_{50} is a catalog throw value to a terminal velocity of 50 fpm. A throw value can be selected using a catalog performance table by multiplying the desired throw ratio (T_{50}/L) by the characteristic length (L). The throw ratio is based on a 9 ft. ceiling height. The throw can be increased or decreased by the same amount that the ceiling height exceeds or is less than 9 ft.

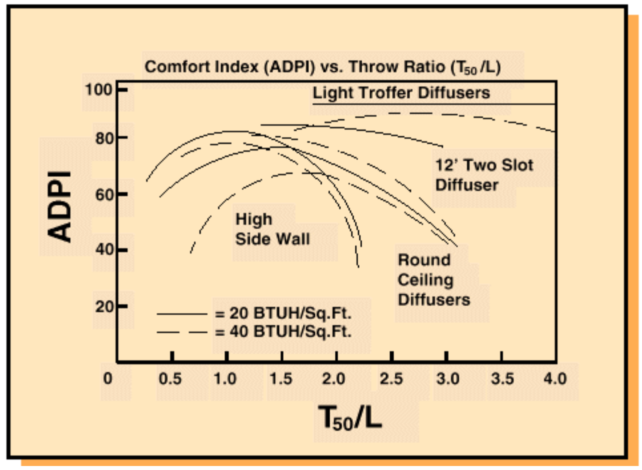


Figure 1: Diffuser ADPI curves.

To obtain optimum comfort in the space, ADPI tests indicate selecting the outlet from the throw ratios in **Table 1.** These data are reported in the ASHRAE *Fundamentals Handbook*, Chapter 31, Table 2. They are based on a relationship between isothermal throw and ADPI under load. These data represent a typical load of about 20 Btuh/SqFt, and represent about 20° ΔT at 1 cfm/SqFt for most applications.

Device Type	T_{50}/L For Max.	Max ADPI	Range of T_{50}/L	For ADPI >:
Grille	1.5	85%	1.0 - 1.9	80%
Round	0.8	93%	0.7 - 1.3	90%
Slots (T_{100})	0.3	92%	0.3 - 1.5	80%
(T_{50})	0.5	92%	0.5 - 3.5	80%
Troffers	1.0	95%	<4.5	90%
4-Way	1.0	95%	1.0 - 3.4	80%

Table 1: ADPI Range

ADPI may be predicted from Table 1, or may be tested using the procedures outlined in ASHRAE Standard 113-90. This test standard was developed to verify performance for some GSA projects in the late 1970s, and has been used to document the results of many air distribution systems. The validity of the relationship between Isothermal T_{50} and room length has been consistently verified.

Using this test standard, and modern computer graphics capabilities, room draft temperature profiles have been generated which illustrate well the movement of air and temperature gradients in a room. Figure 2 is just one example of a temperature velocity profile generated using the ASHRAE 113 procedure and a PC-based data acquisition system.

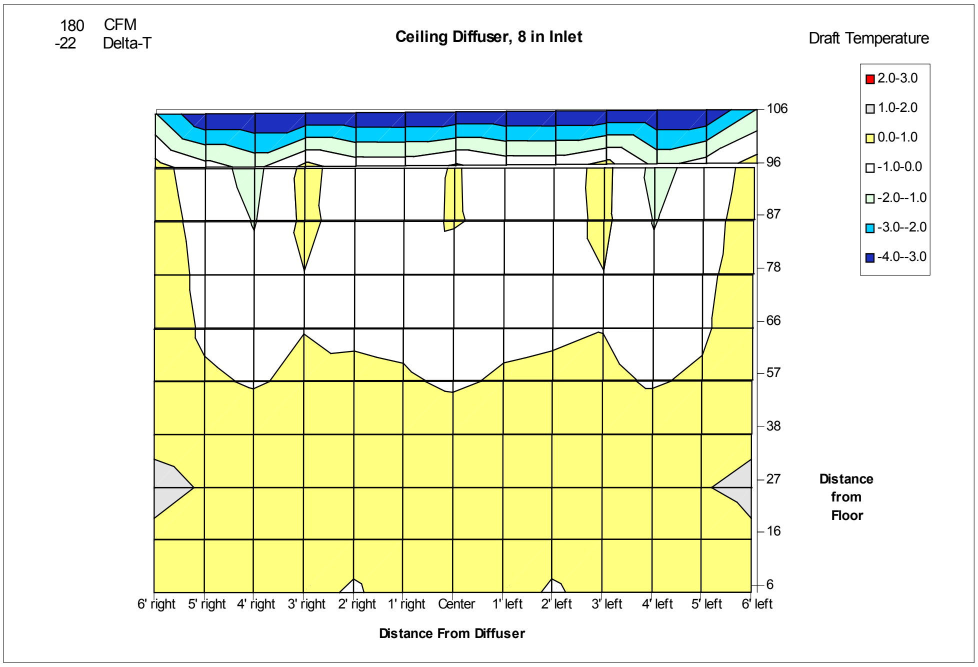


Figure 2- Draft Temperature Profile

ADPI vs. Air Change Effectiveness (ACE)

ASHRAE has recently defined a term for describing the mixing of supply and room air, replacing the somewhat ambiguous terms Ventilation Effectiveness and Ventilation Efficiency with a new term, Air Change Effectiveness, or ACE. This term is used in both ASHRAE Standard 129, the Method of Test for Air Change Effectiveness, and in the public review draft (recently withdrawn) to ASHRAE Indoor Air Quality Standard 62-89R.

The relationship between ADPI and ACE has not been fully evaluated at this time, but the data available at present indicate that if a high ADPI is attained, the ACE will also be high. While there have been no reported tests where the ACE was significantly below 100% when cooling from the ceiling, it has been demonstrated that in heating mode the ACE may decrease significantly.

The ASHRAE IAQ Standard, 62-1989, assumes a ventilation mixing of 100% in setting minimum ventilation rates. If it can be shown that the ACE is less than 100%, then the amount of outside air must be increased above the required minimums. With presently available information, when a high ADPI is measured, the ACE is high as well. For this reason, the next revisions of the ASHRAE IAQ standard (now under continuous maintenance) will likely recommend diffuser selection based on ADPI in order to ensure acceptable ACE. It is possible, however, to have a high ACE and a low ADPI, especially if the HVAC system air is supplied directly into the occupied zone. Uniform comfort will not be likely in this case, however.

Cooling Selection Based on ADPI

ADPI is intended as a measure of performance in cooling mode. When in heating mode, the ADPI criteria often become overly sensitive to temperature differences (due to the very low air speeds present in heating mode), and as a result ADPI is not a good means of performing heating evaluations. Heating is best analyzed as a function of vertical temperature gradients as compared to ASHRAE 55's requirements. Interior spaces, however, are predominantly in a cooling mode of operation so this limitation is seldom a problem in interior zone evaluations.

ADPI Selection Procedure, Classical

A typical procedure for using ADPI to select a diffuser size, is as follows.

1. Select type of diffuser.
2. Check Manufacturer's recommendations to determine if the diffuser's jet pattern will have excessive drop at the desired flow rate, using ceiling height as a parameter. (The jet should not penetrate the occupied zone)
3. Select the characteristic length (L) from the plans. This is the distance from a diffuser to a wall, or to the centerline between two diffusers, etc.
4. Determine the desired diffuser (isothermal) throw using the characteristic room length and the throw ratio from **Table 1.**
5. From the manufacturer's performance table select a size with a T50 within range for the diffuser at the required cfm
6. Check sound levels for NC compatibility and excessive pressure drop.
7. With VAV systems, one should now recheck the analysis at the expected minimum occupied flow rate.

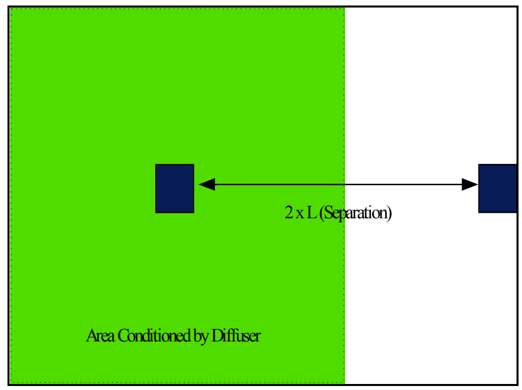
This selection will result in maximum comfort for the application. In the event that this selection cannot be made as outlined, supply jet mapping can be used to determine the discomfort areas in the space.

ADPI Selection Procedure, CFM/SqFt.

Selecting for ADPI in each room can be tedious, and may not be possible at the time of diffuser selection as the room layout may not be known (moveable full height partitions and walls may lead to uncertainty about final zoning). In addition, when VAV systems are employed, the diffuser must be selected which operates at both design flow rates (typically at designed maximum loads) and at reduced load and flow rate. As an alternative to determining the T_{50}/L for each room and load, it is possible to determine some characteristic curves for different diffuser types based on the airflow rate/unit area. This allows an "operational envelope" to be predicted for different diffuser types.

The process requires that a typical diffuser supply area be defined, and this area be combined against a flow rate/unit area and the diffuser's throw performance, and the result plotted on a graph. When this is done, the envelope of acceptable operation of a diffuser based on CFM/sq. ft. is presented.

The diffuser spacing is twice the value of 'L', or equal to the (average) distance between the diffuser and the adjacent wall. The area served



by a 4-way pattern diffuser is therefore $(2xL)^{2.}$

Figure 3: Diffuser area and Characteristic Room Length.

An example is shown, in Figure 4. In this graph, the x axis is flow rate/unit area, and the y axis is half the separation distance, or L, the characteristic room length. The horizontal curved lines are simply calculations of flow vs. area served, while the vertical boundaries are computed from the ASHRAE maximum and minimum T_{50}/L ratios for this type of diffuser. Performance within the area bounded by the lines should achieve an ADPI of 80% or greater.

This example shows the performance envelope of a perforated diffuser with a load resulting from a room/supply differential of $20^{o}\Delta T$. Different delta-t's will result in different load rates, and will change the location of the vertical boundaries somewhat.

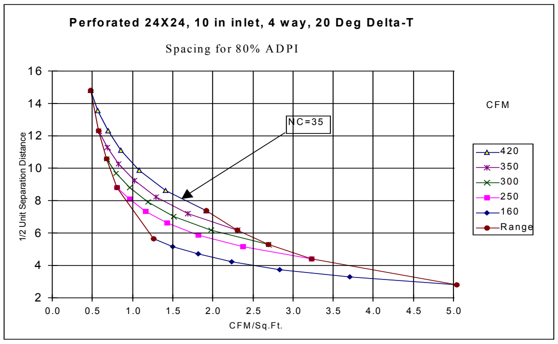


Figure 4: CFM/SqFt chart for a Perforated diffuser.

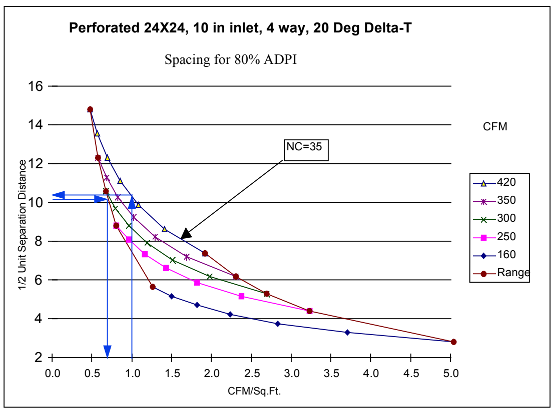


Figure 5: Selection using the envelope chart.

An example of a design selection is shown with the arrows. Starting at 1 cfm/sq. ft, the engineer will proceed upward to the design flow rate (420 CFM) yielding an NC = 35. Then the engineer will proceed to the left to determine the recommended separation distance. The intersection is between 10 and 11 ft, thus the diffusers should be located 20 to 22 ft apart.

The engineer can determine the allowable turndown with this design. Tracing the horizontal path to the leftmost edge of the defined 80 ADPI zone, and proceeding down to the X-axis, the minimum cfm/sq. ft can be seen to be about 0.7 with this diffuser .

A procedure to calculate diffuser spacing using these charts would be as follows:

1. Determine the cfm/sq. ft range for the space based on loads and desired supply temperatures. (Minimum flow rate should be based on occupied minimums, not ventilation minimums.)
2. From the 80% ADPI range charts for a given diffuser (a number of these are provided below), select a diffuser type that works over the range of expected air flow rates, checking at both maximum and minimum occupied rates.
3. Check Manufacturer's recommendations to determine if the diffuser's jet pattern will have excessive drop at the desired flow rate, using ceiling height as a parameter. (The jet should not penetrate the occupied zone)
4. Check product performance tables sound levels for NC compatibility, and check for acceptable pressure drop.
5. Determine diffuser spacing from selected chart.

Attached are examples of a number of diffuser types presented as flow rate Vs spacing:
4 way pattern diffusers:

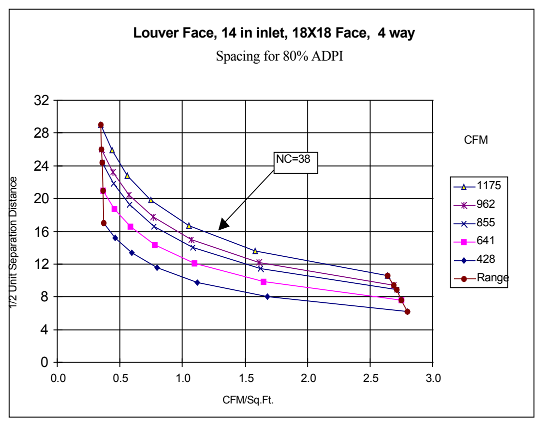


Figure 6: Louver Face Diffuser

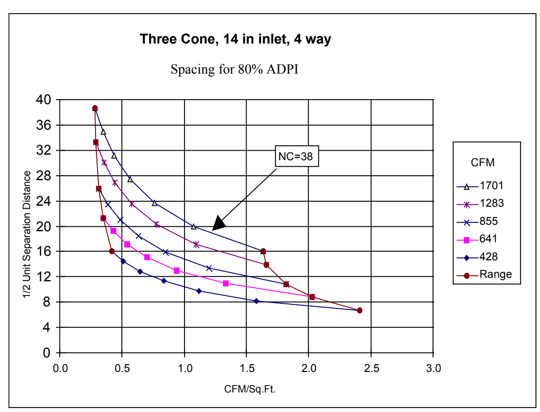


Figure 7: 3 Cone Diffuser

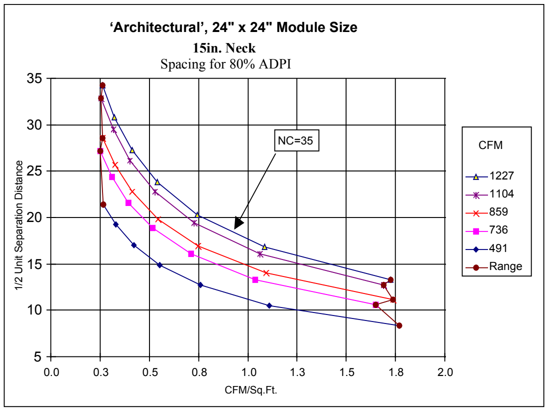


Figure 8: Architectural Diffuser

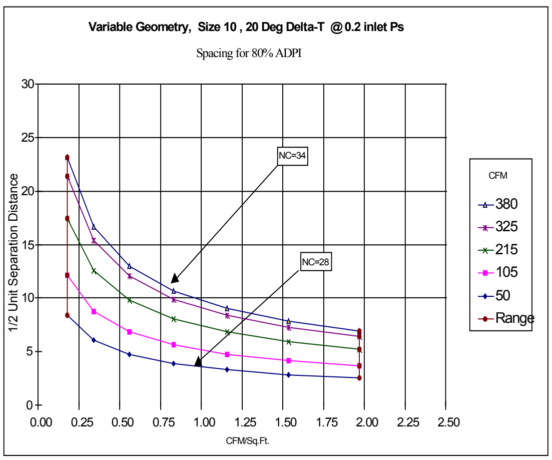


Figure 9: Variable Geometry Diffuser

Analyzing these charts, it can be seen that they have quite different 'turn down' limits. The perforated diffuser shown has quite a high flow capability, but can't be used below 0.7 cfm/SqFt. On the other hand, the others shown will operate down as low as 0.2 cfm/SqFt (variable geometry), but are limited above 1 cfm/SqFt. at this separation. If different neck areas are analyzed, a different separation distance results, but it will be seen that the flow/unit area limits don't change appreciably.

Linear Diffusers:

For linear diffusers (or any one or two-way pattern diffusers), the analysis is a little different. The side to side spacing becomes a variable in the equation, and the result is a graph with multiple X-axis.

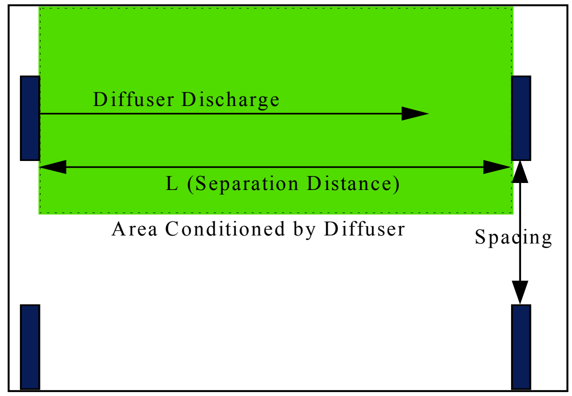


Figure 10: Linear Diffuser Area Relationships.

The CFM/SqFt. must be selected with the side-to-side spacing as a parameter. With an 8 ft spacing, the above diffuser can be shown to be able to operate down to 0.1 cfm/SqFt.

Note that ASHRAE's selection chart uses the 100 fpm throw (T_{100}) as the selection criteria for linear diffusers.

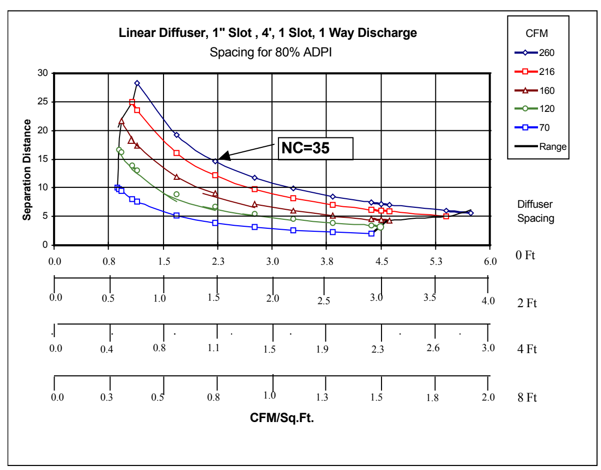


Figure 11: Linear Diffuser (1 way pattern shown).

Selecting diffusers using the above charts will result in selections that meet the requirements of the ASHRAE Handbook of Fundamentals. Experience has shown that when these guidelines are followed, excellent air distribution, uniform temperatures and no objectionable drafts should be expected in the space. Providing that acceptable temperatures are established as a function of the occupant's clothing and activity levels, occupant comfort should be assured as well. Indoor Air Quality, which is many times a perception issue, will be assured as well.

Office space layouts are often revised in response to changing needs, reorganizations, and changing tenants. When space use changes are anticipated, diffuser selections should be reconsidered, as well. Significant changes in required airflows may push the installed diffusers out of their recommended operating range, and full height partitions may require reanalysis of the room's characteristic length.

It should be noted, however, that several published research papers have shown the 5 or 6 ft high partitions (in a 9-ft. high room) do not adversely affect air circulation if the diffusers meet the ASHRAE ADPI criteria. The heat loads generated in cubicles create convection circuits that mix the air fairly well. If the diffusers, however, have excessive drop, or if there is insufficient mixing at the ceiling due to low airflows or diffuser throws, then localized regions of discomfort can result, regardless of the partition height.

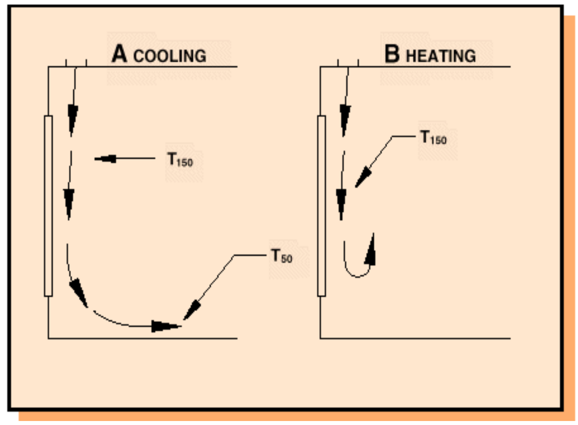
Perimeter Diffuser Selection:

The selection of diffusers in a perimeter zone is less predictable, as it depends to a great deal on the actual window-wall geometry. In perimeter applications, concerns focus mainly on heating. However, it is also well understood that the air conditioning system must handle both heating and cooling. Both heating and cooling the perimeter can be handled best from diffuser locations in the lower part of the exterior wall. Economic reasons, however, favor heating and cooling from overhead. Several main approaches have been utilized for the ceiling heating and cooling distribution.

A system that must both heat and cool a perimeter zone will exhibit quite different air jet performance in heating than in cooling. Winter cold airs down drafts exist at the perimeter and may affect persons or equipment, and must be treated by the diffuser to prevent complaints of cold discomfort.

All air overhead systems therefore must offer a compromise between heating and cooling demands.

A 'rule of thumb' for estimating the effect of downward projection of air at 50 fpm, is that the



isothermal throw is increased or decreased by 1% per Deg.F Delta-t, (with cooling throw increasing).

Figure 12: Vertical air patterns in heating and cooling.

Sills tend to deflect cold air and project cold air horizontally into the room at that level. The cold air continues on to the floor level, and the warm air turns back up toward the ceiling. This action increases as the sill width increases. As the sill height increases so does the height of the stratification layer.

Generally, 50% airflow to the window and 50% to the room is recommended. However, some adjustments to the flow are beneficial, so adjustable diffusers are preferred.

Air directed at the window will mix with room air and the cold air that forms next to cold glass. The higher velocity air is not affected by the supply air / room temperature differential. Slower velocities, however, are significantly affected, with warm air tending to rise back up towards the diffuser. In cooling, however, the cold air falls and proceeds along the floor.

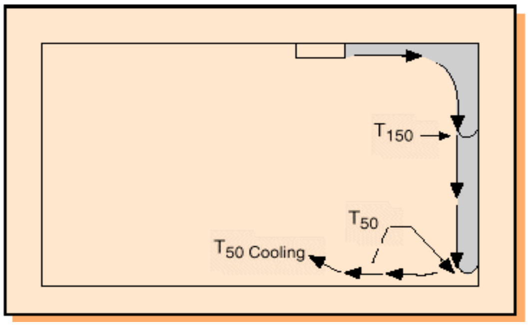


Figure 13: Diffuser directed at exterior wall.

In a closed office, it may be desirable to 'roll the room'. In this circumstance, a high induction (high discharge velocity) diffuser (typically a linear diffuser) is used to direct air away from the window directed towards the back wall of the room.

If the glass heating load is high (> 200 BTUH/Linear Ft. of wall), some additional heated air should also be directed towards the glass to counter the cold air draft created by the window.

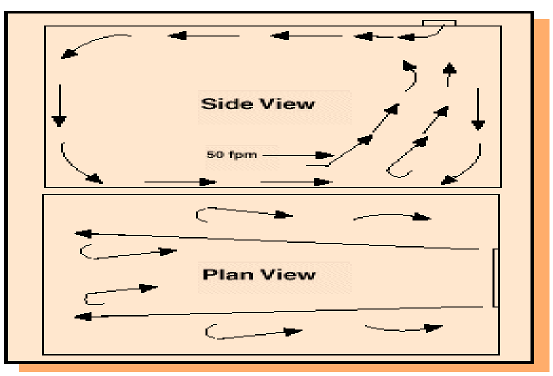


Figure 14: Rolling The Room.

When a 1 to 2 ft. soffit is above the window area, heating with an outlet back from the soffit cannot be used. The air spreads in the soffit and turns up at the bottom of the soffit to return to the outlet. High levels of stratification then occur. With a soffit, vertical projection from below the window must be used, or a ceiling diffuser utilized whose jet can be directed under the sill.

The ASHRAE Handbook Fundamentals, 1993, Chapter 31, recommends that temperature differentials between heated primary air and room air should not exceed 15–20° F so buoyancy effects are minimized. In addition, there is data that indicates that high delta-t's result in poor Air Change Effectiveness (ACE), as low as 30% in one documented case. It should be assumed that in the future there will be a requirement for the demonstration of heating Air Change Effectiveness, and that the higher the delta-t, the more outside air will be required to offset the reduction in ACE.

This will pose a problem with many types of rooftop units—specifically gas fired ones—and high airflows will be required both to prevent stratification and increase ventilation, with attendant increased costs of operation. With these systems, typically the heating is cycled and stratification is broken up, but this doesn't necessarily solve the potential IAQ problem. Analysis of modern building loads will show that with 1 cfm/SqFt. the required delta-t to handle loads is usually less than 10^{o}F during occupancy.

Another approach is to use a split system with a minimum constant volume of air to satisfy the perimeter windows or walls. A variable volume type system with a regular diffuser handles the additional cooling. The split system results in a more satisfactory comfort level for both cooling and heating. It can be used in a closed office or open plan arrangement.

Typically, each perimeter situation must be considered as a unique design situation. Often, testing a mock-up is a good decision for large projects where after-installation modifications would be expensive. To date, using a CFD (Computational Fluid Dynamics) analysis, while in theory an excellent tool, has not yet been proven to be a reliable tool.

Rather, a 'cold wall' is set up with the perimeter geometry duplicated and actual outside air temperatures established, and detailed room temperature / velocity profiles measured and recorder in accord with ASHRAE Standard 113.

In addition, smoke photos and actual occupant exposure can be used to gain confidence in a given solution to the unique engineering situations that occur at each perimeter design.

Shown in Fig15 is a plot of temperatures from a test of a room with a 0^{o}F outside air temperature, and a two way discharge diffuser located two feet from the glass, with 10^{o}F Delta-t and 1 cfm/SqFt., conducted per ASHRAE Standard 113-90.

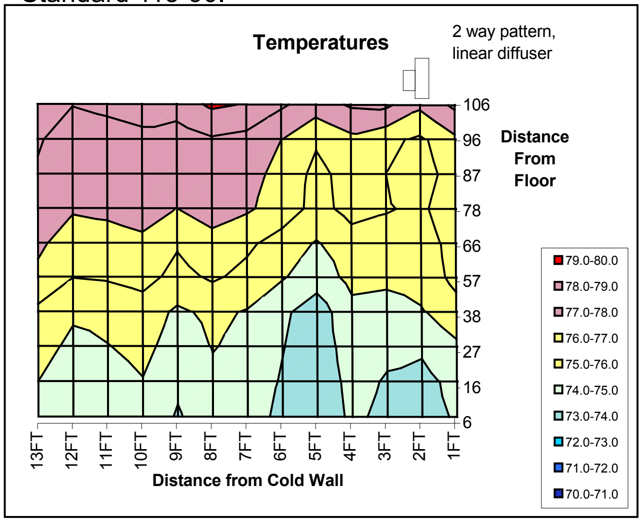


Figure 15: Perimeter Single Plane Temperature profiles.

The tests shown in Fig 15 meets ASHRAE Standard 55 Comfort requirements.

Summary:

Diffuser selection is becoming recognized as a critical problem in avoiding problems with a building's design. Designing in accordance with ASHRAE's recommendations is a sure way of avoiding the creation of a 'litigation rich environment'. The Handbook of Fundamentals, chapter 31, along with manufacturer's recommendations and guidelines, provide tried and tested ways of designing to avoid complaints or problems. Failure to select diffusers with regard to proper design can result in discomfort and concerns over poor indoor air quality.

Diffusers are created with specific performance parameters inherent in each design. These parameters need to be understood, and used in selecting the size and type of unit for each situation. Recent court cases have shown that the engineer can no longer allow the Architect to make the decision on diffuser selection based on appearance alone. Architects and Engineers need to cooperate to ensure that all their need are met.