A Design Solution to Improve Heating Performance of Pressure-Independent Terminal Units

Connected supply air devices are the last place that anyone looks.

By Francisco Valentine, P.E.

Introduction

Poor heating performance in single-duct pressure-independent terminal units is a much more pervasive problem than we would like to admit. Heating problems tend to present themselves during the winter and shoulder seasons. It can affect any Variable-Air-Volume (VAV) air-handling unit and air distribution system that conditions zones with perimeter and/or roof loads. The typical scenario consists of a VAV terminal unit (also referred to as VAV Box) that cannot warm the space to setpoint even though the heating is at maximum capacity. This problem is often thought to be a control or balancing issue, but this is not the case.

When the Building Automation System (BAS) is reviewed (Figure 1), the VAV terminal unit supply airflow is at setpoint (typically minimum), the heating control valve is typically wide open (or electric heat at full capacity), discharge air temperature is high (85°F or higher), yet the space temperature is well below setpoint. When the airflow calibration is checked, the proper amount of supply air is provided. The high discharge air temperature indicates that we have adequate heating capacity. The VAV box controller is doing exactly what is required by the mechanical design (sequences of operation). If the terminal unit is functioning properly, why is it not heating the space?

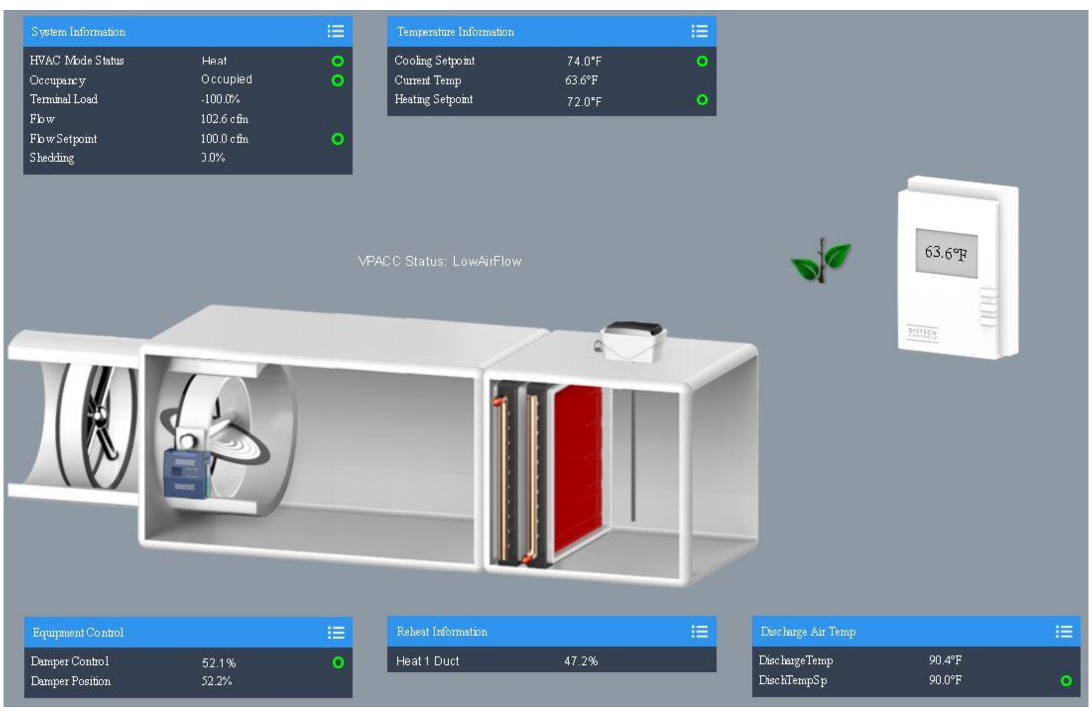
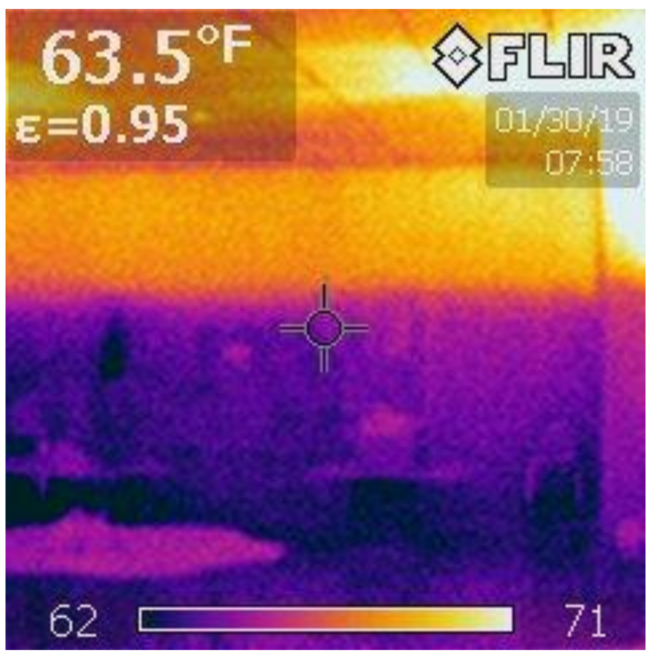


Figure 1 – Typical VAV Terminal Unit Graphic

This is a question commonly posed to most Controls Contractors who operate in latitudes subject to freezing conditions. They can offer slight improvement in the operation with setpoint changes, but they cannot overcome the shortcomings of the mechanical design. The typical short-term solution is to set the air-handling unit to enable earlier in the day or even run 24/7. However, this is wasteful from an energy standpoint and is merely a bandage for the real problem. Another short-term solution is to raise the heating airflow setpoint of the terminal unit. This helps to improve room air mixing, but the hydronic or electric heating coil is typically sized to heat the design minimum airflow. As a result, there is no appreciable increase in heat transfer to the space. These measures do little to improve the space conditions.

When asked to determine why the classrooms in the newly renovated wing of an elementary school were not adequately heated, a field investigation ensued. The following photograph shows a classroom that was photographed with an infrared camera during the winter of 2019. This is the best infrared image that I have ever taken that so clearly shows room temperature stratification. A pocket of hot air resides at the top level of the room and extends down approximately four feet from the ten-foot ceiling. The infrared image was taken of the interior wall. The scale at the bottom of the infrared image shows a temperature range of 62°F to 71°F. However, we must keep in mind that this represents surface temperatures – not air temperatures. You need only climb a ladder to the top of the room to verify temperature stratification. The infrared image shows that the air temperature stratification was enough to significantly impact surface temperature of the wall. The air temperatures at the top of the room ranged from 85°F-90°F while the air temperatures at the floor level were between 60°F-65°F. The space temperature sensor was located at approximately 4.5 feet above the floor (below the heat cloud).



Photograph 1 – Classroom Infrared Image

The infrared image clearly indicates that the discharge velocity from the supply air devices is not high enough to fully mix the room air and eliminate air temperature stratification. In elementary schools, the students occupy the space below the heat cloud (~6 feet). Kindergarten students spend a lot of time on the floor with group activities, so they are exposed to the low air temperatures. This is a wide-spread problem that is largely unknown. Occupants served by these problem supply air diffusers have learned to deal with it because a feasible solution has never been presented.

Single-Duct VAV Terminal Units

Single-duct VAV terminal units are typically controlled by a Direct Digital Controller (DDC) controller that uses a zone temperature reading as its principal control variable to determine how it functions. The typical single-duct terminal unit consists of an airflow pickup, control damper, reheat coil, control valve (for hydronic systems), and controls enclosure. The airflow pickup may be in the form of a cross or a ring. The differential pressure caused by the supply air flowing over it is measured by the VAV box controller. Manufacturers provide K-factors that relate the measured differential pressure to airflow. The supply airflow is calculated from the measured differential pressure and K-factor. The control damper is modulated by an electric (or pneumatic) actuator to maintain the supply airflow rate between the programmed minimum and maximum airflow setpoints. The control valve controls the flow of hot water through the reheat coil to provide space heating when required. An electric reheat coil may be used in lieu of a hydronic coil to provide heating capacity.

There are typically two main operating modes for VAV terminal units - Heating and Cooling. Additional functions like space temperature setpoint override, occupancy override, demand-controlled ventilation, and stand-by modes are possible. In cooling mode (refer to Figure 2), the flow of supply air is modulated between the minimum and maximum cooling airflow setpoints to maintain the space temperature at the cooling setpoint. The heating and cooling space temperature setpoints are typically 2°F to 6°F apart to prevent unnecessary mode changeovers. For example, the heating space temperature setpoint is often 70°F while the cooling setpoint is often 72°F to 76°F.

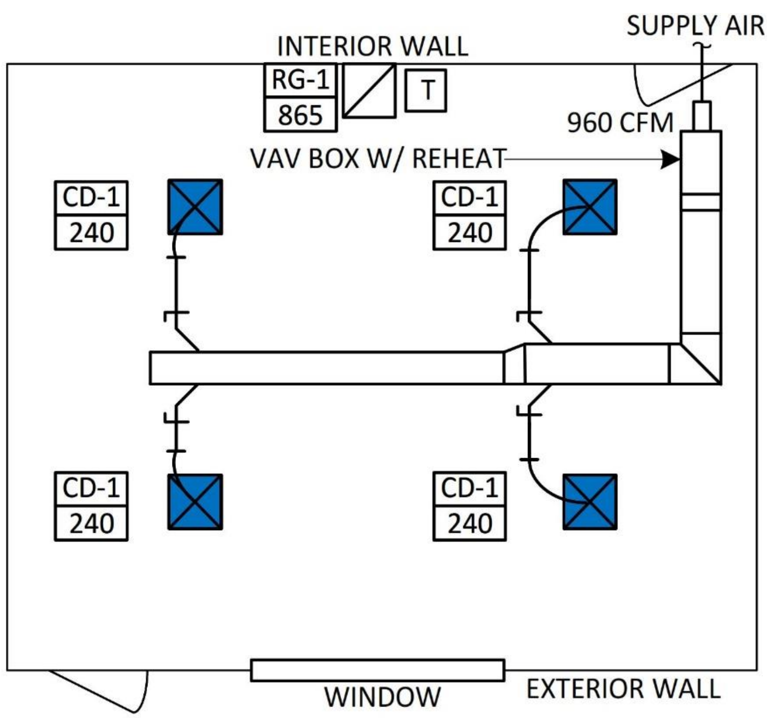


Figure 2 – Typical Terminal Unit Schematic – Cooling Mode

If the cooling load falls below the minimum cooling capacity provided when the VAV box operates at its minimum airflow setpoint, the space temperature will continue to drop until it reaches the heating space temperature setpoint. At this point, the heating mode is enabled. Heat is typically supplied by either a hot water coil or an electric resistance coil while operating at the minimum supply airflow setpoint (Figure 3). Some sequences of operation allow the heating airflow to increase to a maximum heating airflow setpoint which could be as high as the maximum cooling airflow setpoint. However, the maximum heating airflow setpoint in the vast majority of VAV systems is typically equivalent to the cooling minimum airflow setpoint.

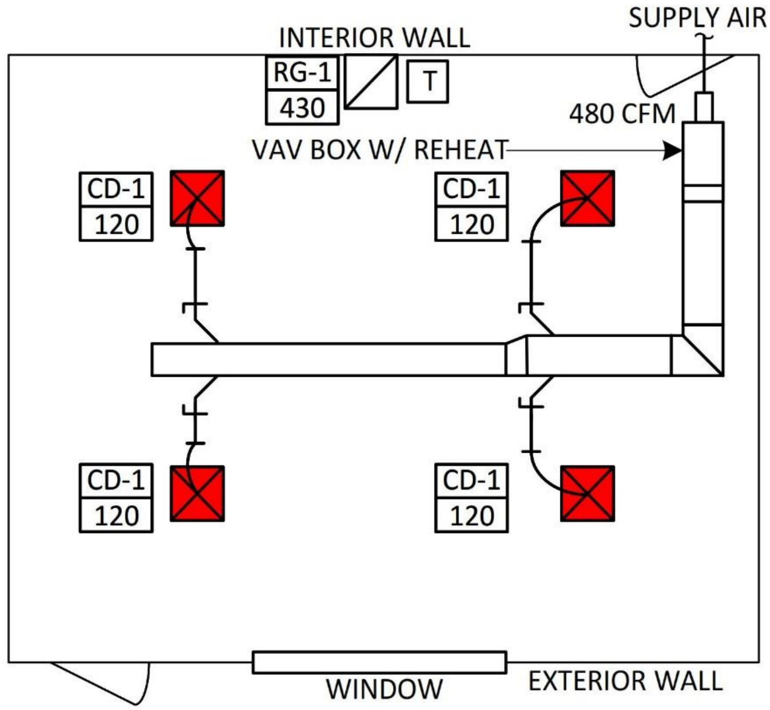


Figure 3 – Typical Terminal Unit Schematic – Heating Mode

Interior and perimeter zones have quite different cooling and heating characteristics. Interior zones are defined as spaces that have no exterior walls. Perimeter zones are those spaces that are subject to heat gains and losses through the perimeter walls, windows, and doors. These same spaces may also have a roof load, but the heat gains and losses through the roof are typically much lower than through the perimeter walls because of the higher insulation ratings used in its construction.

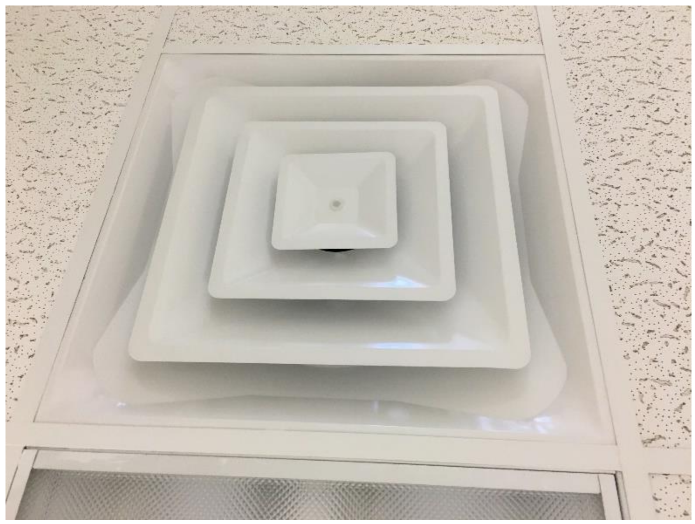
Interior zones typically require very little heat to maintain the space temperature in the desired range throughout the year. The interior heat gains from people, lights, and equipment will often require year-round cooling. As such, terminal units serving interior zones may not even have heating coils. However, terminal units that serve perimeter zones will almost always have a reheat coil to maintain the space temperature at setpoint during cold weather.

At outside air temperature extremes, the surface temperatures inside the perimeter walls, windows, and doors can be significantly higher or lower than the room air temperature. This temperature difference can generate convective air currents along these perimeter surfaces which may feel like drafts. The convective air current will be downwards during the winter as cold air drops and upwards during the summer as warm air rises. A correctly selected supply air diffuser will mitigate or at least reduce these convective air currents and their effects on occupant comfort.

Room air mixing while operating in the cooling mode is much more forgiving because the supply air is cool (typically between 55°F and 60°F). At this temperature range, the supply air will naturally drop into the occupied zone even while delivering low airflow rates because the supply air has a higher density than the room air (typically between 70°F and 75°F). Conversely, in the heating mode supply air temperatures from the VAV boxes can be in the 80°F to 105°F range. At these temperatures, the supply air is much more buoyant and will tend to rise and collect at the top of the room. When buoyancy is combined with low supply airflow (and resulting low discharge velocity), this results in the formation of a "cloud" or pocket of hot air at the ceiling level. This is a sign that the heating airflow for the installed supply air diffusers is too low to provide adequate room air mixing to avoid temperature stratification.

Supply Air Diffusers

Most Heating, Ventilation, and Air-Conditioning (HVAC) systems used in commercial, medical, and industrial applications deliver the conditioned air through overhead air distribution systems. The key to the success of this design is the mixing of the room air to create a homogeneous environment from ceiling-to-floor and wall-to-wall that is free of hot and cold spots as well as drafts in the occupied zone. Air distribution systems utilize the supply air jets created by carefully located and properly selected Diffusers, Registers, and Grills (DRGs) to mix the room air. When the supply airflow rate changes, as is typical of a VAV system, the level of room air mixing can be significantly affected.



Photograph 2 – Titus Four-Way Supply Air Diffuser

Supply air diffusers are responsible for delivering the conditioned air to the occupied zone during both heating and cooling operation. They are also responsible for mixing the room air sufficiently to prevent temperature stratification. Photograph 2 shows a typical four-way supply air diffuser in a suspended ceiling grid which generates four discharge jets in orthogonal directions. The occupied zone is defined by American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 55 – Thermal Environmental Conditions for Human Occupancy to be the volume of air that is contained by a vertical boundary of six feet above the floor, 3.3 Feet from the exterior walls, and one foot from the remaining interior walls of the room (Figure 4).

The system designer typically selects the supply air DRGs based on the maximum cooling airflow rate taking into account the resulting noise level, room dimensions, and required throw values. The manufacturer provides performance data (throw, noise level, pressure drop, etc.) for all DRGs they provide to aid the designer in the selection of supply and return air devices. DRG selection strategies vary and can depend on what DRG manufacturer the designer prefers as their basis of design. The Titus Grills and Diffusers Engineering Guide provides a DRG selection procedure based on the Air Diffusion Performance Index (ADPI). This procedure is used by many mechanical designers.

Regardless of the selection method used, it typically results in acceptable cooling performance because the cool supply air will drop into the occupied space. However, it is more difficult to predict the performance of supply air diffusers while operating in the heating mode because the heating airflow rates are typically much lower and the heated supply air is buoyant. In some mechanical designs, the terminal unit minimum supply airflow setpoint can be as low as 30% of the maximum which almost ensures that the supply air diffuser performance in heating mode will be poor. DRG performance tables document this assertion.

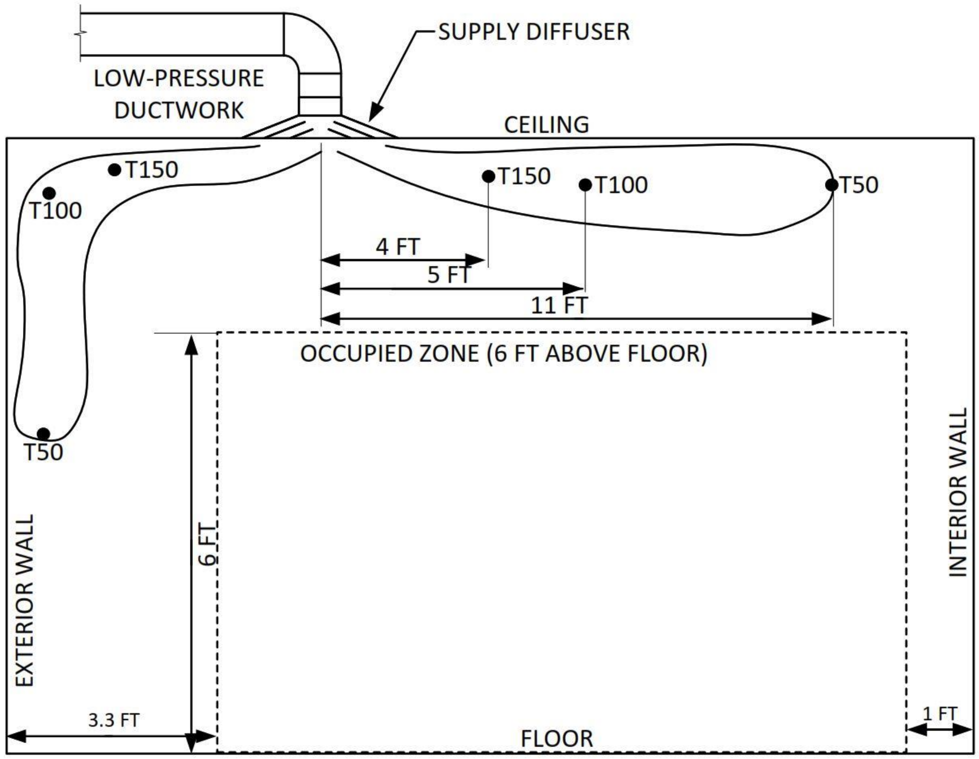


Figure 4 – Typical Room Cross-Section

Throw is a variable in the DRG performance data which describes the distance in Feet from the device at which the supply air has reduced to a certain reference terminal velocity. Most performance data tables provide reference throw data at terminal velocities of 150 Feet Per Minute (FPM), 100 FPM, and 50 FPM which are designated as T150, T100, and T50, respectively (Figure 4). It is also important to note that these terminal velocities are measured at isothermal conditions which means that the supply air temperature was neutral during their testing - not heated or cooled. Actual throw values of cooling supply air will be lower than the indicated values. Likewise, actual throw values of heated supply air will be higher than the indicated values.

As the supply air jet discharges from supply DRG, its velocity is high which induces or entrains the room air into the air stream in the direction of flow (Figure 4). As it progresses, the induced air and primary supply air streams continue to mix creating a larger flow of total supply air. The velocity of the total supply air stream decreases along its path of travel. The DRG performance tables provide the results of empirical velocity data derived from thousands of tests. This data is used by the system designer to evaluate the DRG performance given the current design conditions. Because ASHRAE Standard 55 and many diffuser manufacturers recommend a maximum air velocity of 30-50 FPM in the occupied zone, the T50 terminal velocity is typically used to select DRGs.

Diffuser noise is generated by the supply air as it passes through the neck and exits the diffuser. Air velocities must be high enough to entrain and mix the room air to create consistent temperatures throughout the space. However, higher air velocities generate higher noise levels. Too often, the desire for low diffuser noise levels results in supply air diffuser selections that are oversized. This results in very low throw values which provide inadequate room air mixing even at maximum cooling airflow rates. Cooling operation is more forgiving of poor supply air diffuser selections because the cool air will drop into the occupied zone. However, if the same supply air diffusers provide heating service, they will have no chance of adequately mixing the room air because of the significantly lower airflow rates and the resulting low throw values. This highlights the fact that supply air diffuser selection is critically important to providing year-round occupant comfort. HVAC designers should remember that occupants actually prefer some system noise. It's an auditory cue that lets them know that the system is actually working.

For example, suppose that the minimum supply airflow rate is 50% of the maximum cooling airflow. Therefore, if the design maximum cooling airflow is 240 Cubic Feet per Minute (CFM), then the minimum cooling airflow rate is 120 CFM. Suppose further that the heating airflow setpoint is fixed and equal to the cooling minimum supply airflow setpoint. Table 1 provides performance data for the Titus TMS supply air diffuser. The throw data includes the T150, T100, and T50 throw values from left to right.

Airflow (CFM)	118	236
Total Pressure (INCHES W.C.)	0.035	0.142
Noise Criteria (NC)	-	28
Throw (FEET)	2-3-5	4-5-11

Table 1 – Titus TMS Diffuser (6-Inch Neck)

The performance data indicates that at the maximum supply airflow of 240 CFM, the T50 throw will be 11 Feet. Referring to Figure 5, 240 CFM would provide enough throw (11 Feet) to reach the vertical plane of the occupied zone. However, this throw is not high enough to reach the occupied zone. An additional 4-5 Feet of throw is required. The cooling air stream is indicated by the blue line in Figure 5. This is an example of a DRG selection that would not fully mix the room air, but would likely provide acceptable cooling performance based on space temperature. This room will likely have temperature variations depending on the supply air diffuser layout.

When the heating performance of the same DRG is evaluated, Table 1 indicates that 120 CFM will provide a T50 throw of only 5 Feet. This is a significant reduction and its impact on room air mixing is even greater. This throw value is less than half the full-flow throw and is not even high enough to reach the perimeter wall let alone the occupied zone. Thus, it would not provide acceptable heating performance because the room air has no chance of being mixed by the supply air. This will result in temperature stratification of the room. The heating air stream is indicated by the red line in Figure 5.

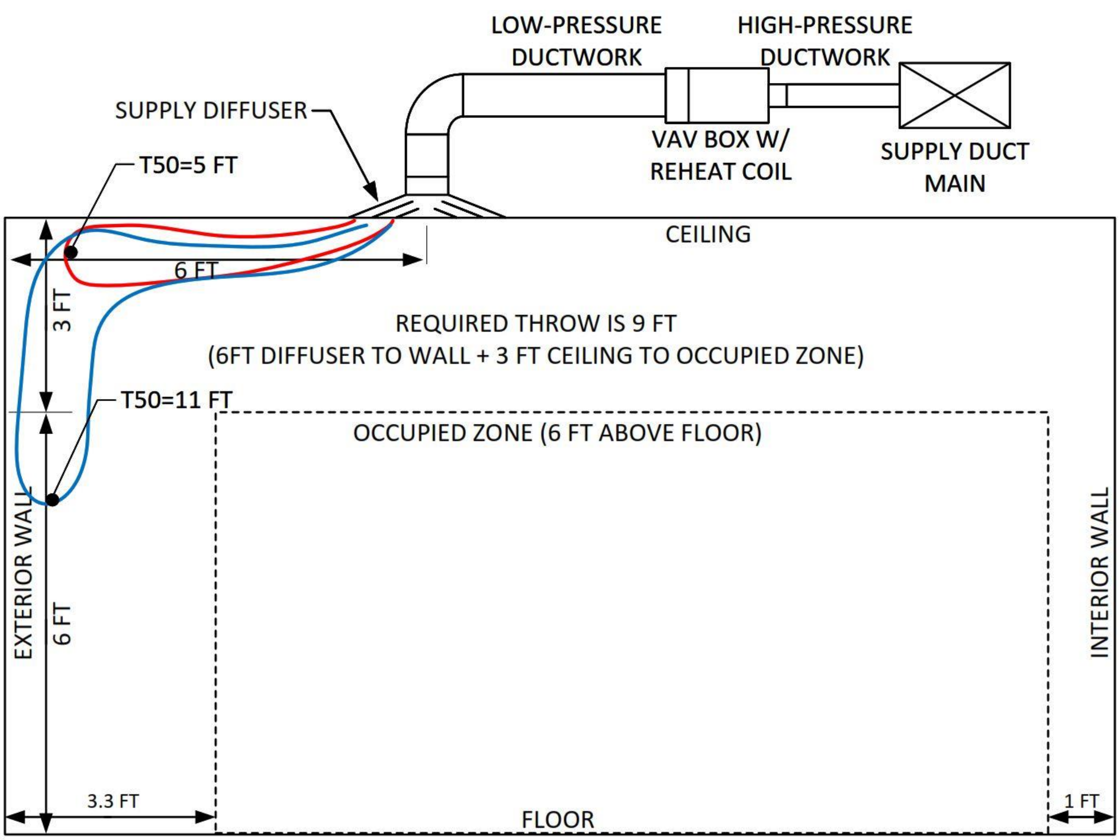


Figure 5 – Heating Throw at Low Airflow Rates

In perimeter applications, it is important that the total air stream (supply air and induced air) reach the occupied zone during both cooling and heating modes. The 3.3 Feet boundary layer defined by ASHRAE 55 accounts for the size of the total air stream and its interaction with the perimeter convective air currents. Therefore, it is recommended that in this perimeter heating example the minimum T50 throw value for the selected DRG type be at least 15 Feet which is the distance from the ceiling-mounted DRG to the wall, plus the distance from the ceiling to the floor as shown in Figure 6.

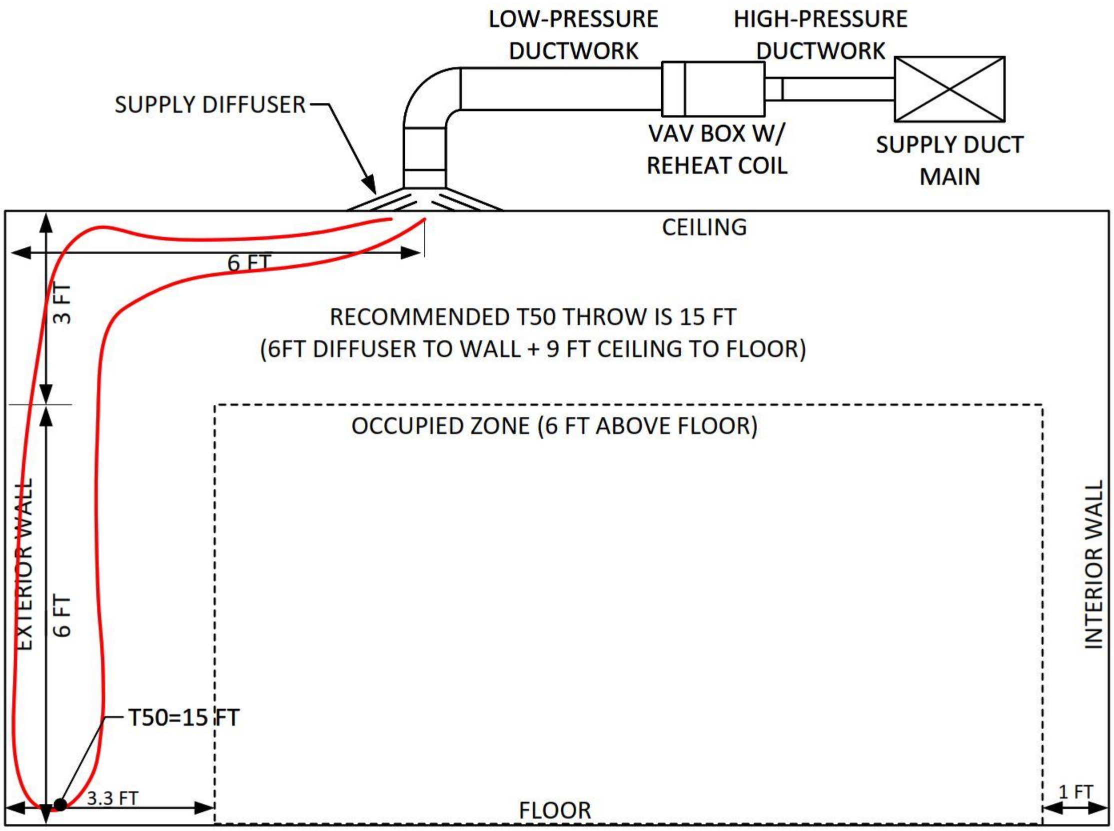


Figure 6 – Heating Throw at Higher Airflow Rates

This will ensure that total air stream reaches the occupied zone, room temperature stratification is minimized, and the air velocity in the occupied zone is below 50 FPM. If the DRG has been chosen based on the maximum cooling airflow setpoint, how will it possibly provide the same performance while operating at the minimum supply airflow setpoint during heating mode? The answer is, “It won’t.” This leads us to the proposed solution which provides an answer to this very problem.

Proposed Solution

The proposed solution is to modify the low-pressure ductwork to accommodate the installation of an additional control damper that isolates a number of supply air devices (Figure 7). By isolating a pre-determined number of supply air diffusers during heating operation, the supply airflow through the remaining active diffusers can be maintained at a high level to provide continued room air mixing thereby eliminating the effects of low supply airflow. During cooling operation, the isolation damper actuator (DA-1) is fully open and the supply airflow provided to the supply diffusers would be no different from a traditionally designed low-pressure VAV duct system.

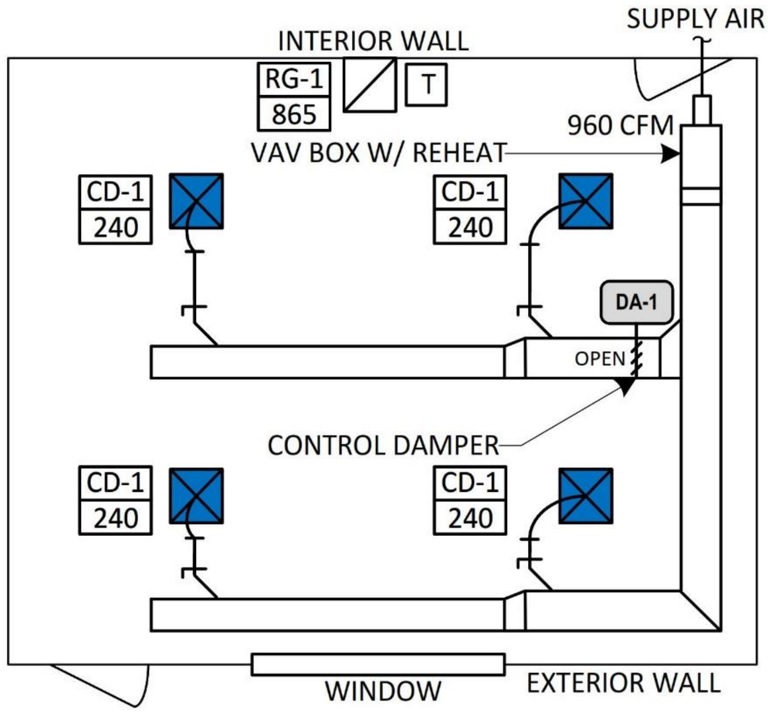


Figure 7 – Terminal Unit Isolation Damper – Cooling Mode

During heating operation, the isolation damper actuator (DA-1) is closed once the heating mode is enabled by the VAV controller which isolates a number of the supply air diffusers (Figure 8). The terminal unit's supply airflow will be at the minimum airflow setpoint. However, because this lower supply airflow is supplied to a lower number of active supply air diffusers, the resulting air-mixing performance is equal to that provided during cooling operation. This solution could be applied to larger spaces served by a higher of number of supply air diffusers. The layout of the isolated and active supply air diffusers can be modified to evenly distribute the heating supply air throughout the conditioned space.

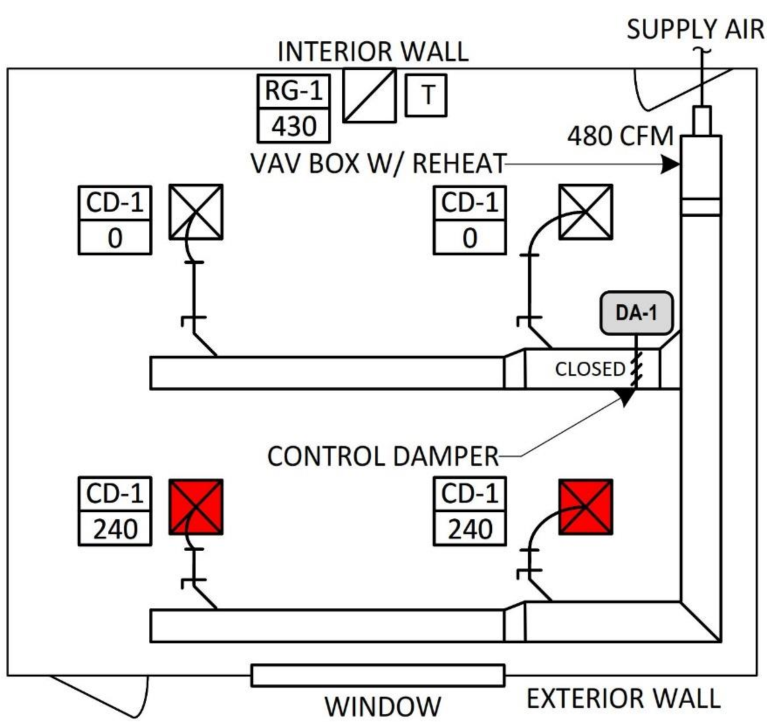


Figure 8 – Terminal Unit Isolation Damper – Heating Mode

Alternatively, a pair of motor-operated diverting dampers could be driven by individual actuators or a common actuator to direct the low-pressure supply air to the cooling diffusers when cooling is required (Figure 9) or to the heating diffusers when heating is required (Figure 10). This allows the system designer to select DRGs for dedicated heating and cooling service instead of selecting supply air devices based on the cooling airflow rate and hoping that they work when heating service is required.

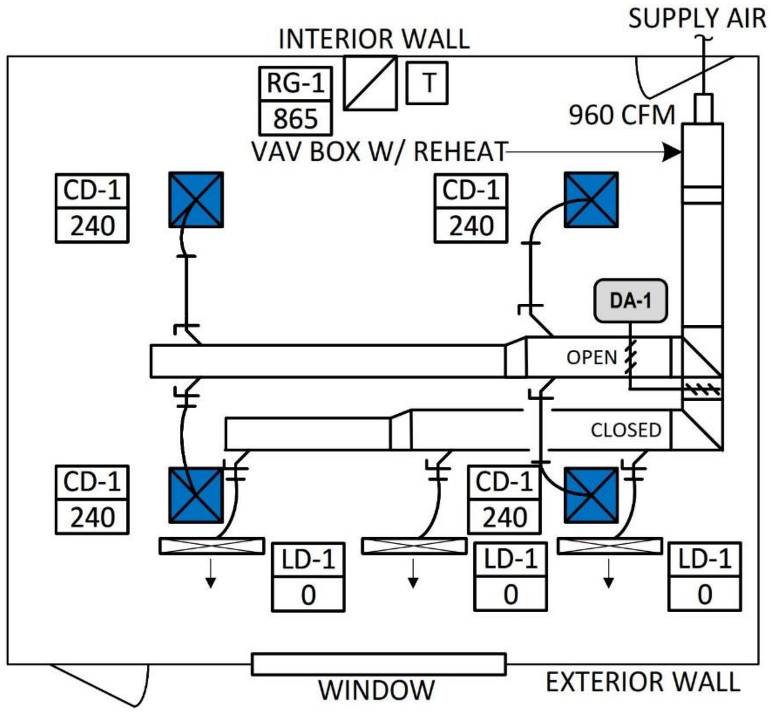


Figure 9 – Terminal Unit Diverting Damper – Cooling Mode

With the diverting damper arrangement, the supply air can be directed to the heating supply air diffusers which have been specifically selected to provide the throw that will mix the room air at the lower airflow rate. In this example, three linear diffusers were selected to better distribute the supply air along the perimeter wall and window (Figures 9 & 10). Linear diffusers are capable of providing much higher throw values than four-way ceiling diffusers for a given airflow rate. With linear diffusers, the T50 distance can be selected to account for the distance from the linear diffuser to the wall and the wall height. This ensures that supply air reaches the occupied zone reducing the potential for temperature stratification. It also provides the exterior wall and windows with a constant stream of supply air which reduces/eliminates convective air currents.

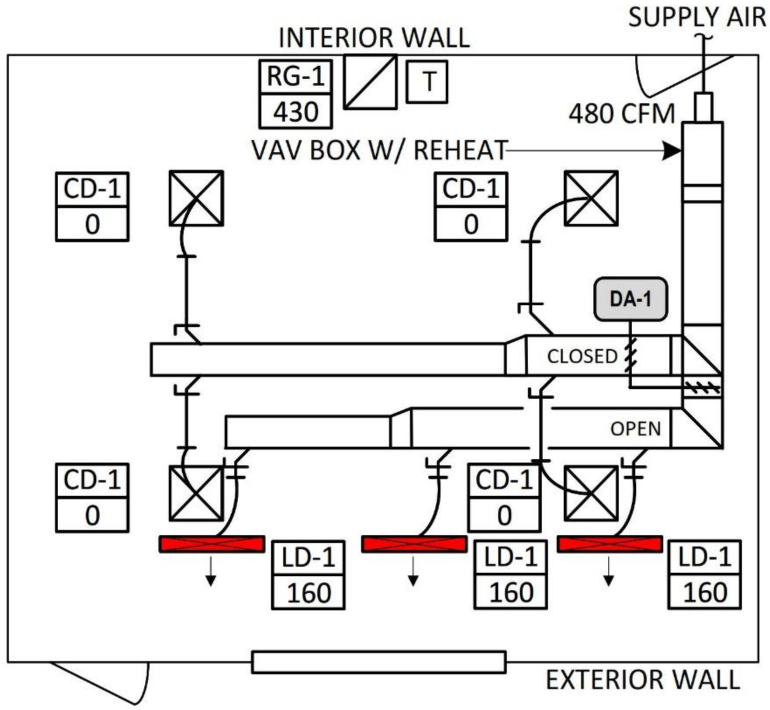


Figure 10 – Terminal Unit Diverting Damper – Heating Mode

Implementation of this solution will minimally increase mechanical costs (when compared to the traditional single-duct terminal unit duct design) because of the additional ductwork, damper, and actuators. Controls cost impact is minimal as there are typically several free binary outputs on the terminal unit controller to control the two-position damper actuator. Commissioning costs will also have a small increase. However, the vast improvement in occupant comfort, productivity, and energy efficiency (eliminate 24-hour operation, reduced supply fan speeds, and reduced reheat requirements) is well worth the additional cost. In addition, it could eliminate or at least minimize the need for electric resistance space heaters and ceiling fans.

Conclusion

The root cause of poor heating performance in single-duct VAV terminal units in perimeter zones can often be traced to the inability of the connected supply air devices (DRGs) to adequately mix the room air while operating at minimum airflow rates (heating mode). However, this is typically the last place that anyone looks because most people do not understand the DRG selection process. If the terminal unit is providing the required heating capacity and airflow and the temperature sensors (space and discharge) are reading accurately, the cause of the poor heating performance must be the supply air devices. They are solely responsible for mixing of the room air to avoid temperature stratification.

Heating issues with pressure-independent terminal units are widespread in northern latitudes. This is very clearly a DESIGN issue to those that understand the DRG selection process. Proper selection of supply air DRGs is critical to mixing the room air to create a homogeneous space condition. This issue highlights the importance of proper DRG selection by the system designer for year-round comfort – not just during the cooling season. This heating isolation damper is a viable solution to the current design process of selecting supply air DRGs based on the maximum cooling airflow requirement and hoping that they perform well enough during heating service.

This solution replaces hope with the ability to provide superior heating performance and occupant comfort even at reduced heating airflow rates. The proposed heating isolation damper solution is simple, energy efficient, and maximizes the heating performance of the active supply air DRGs by maintaining room air mixing even during heating operation. The diverting damper assembly allows different DRG types and quantities to be selected and utilized for dedicated heating and cooling service. This design solution could be implemented as a retrofit, but the impact to the space and the cost will be higher. This solution is best applied during the design phase of a project because the impact of modified low-pressure ductwork and the additional motor-operated dampers is minimal. This solution would compete with series fan-powered VAV boxes which would provide constant airflow, but come at a higher cost and operating expense.

Supply air devices are selected at the maximum cooling airflow rate taking throw, room dimensions, and noise into account. When heating operation is required, the supply airflow rate drops to a lower alternate value that will provide a much lower throw. As a result, they will not mix the room air to prevent temperature stratification. We know the problem very well. The current design approach is not working. We have learned to ignore it and avoid the topic because we lacked a solution. That is no longer the case. Now, we need mechanical design firms with the courage to break from the long-held diffuser selection strategies and cookie cutter designs to implement this innovative solution to provide year-round comfort for the occupants. Who will be the first?

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