3. For all except very noise sensitive applications, select VAV boxes for a total (static plus velocity) pressure drop of 0.5" H_2O. For most applications, this provides the optimum energy balance (see the section below, "Sizing VAV Reheat Boxes").

VAV Reheat Box Control

Common Practice (Single Maximum)

Common practice in VAV box control is to use the control logic depicted in

Figure 21. In cooling, airflow to the zone is modulated between a minimum airflow setpoint and the design cooling maximum airflow setpoint based on the space cooling demand. In heating, the airflow is fixed at the minimum rate and only the reheat source (hot water or electric heater) is modulated. The VAV box minimum airflow setpoint is kept relatively high, typically between 30% and 50% of the cooling maximum airflow setpoint (see Code Limitations").

Advocates of this approach argue that it:

- Insures high ventilation rates.
- Provides adequate space heating capacity.
- Prevents short circuiting due to stratification in heating mode by keeping supply air temperature relatively low (e.g., less than 90°F).
- Prevents "dumping" by keeping air outlet velocities from getting too low.
- Works for all box direct digital controller manufacturers and control types (i.e., pneumatic, analog electronic or digital).

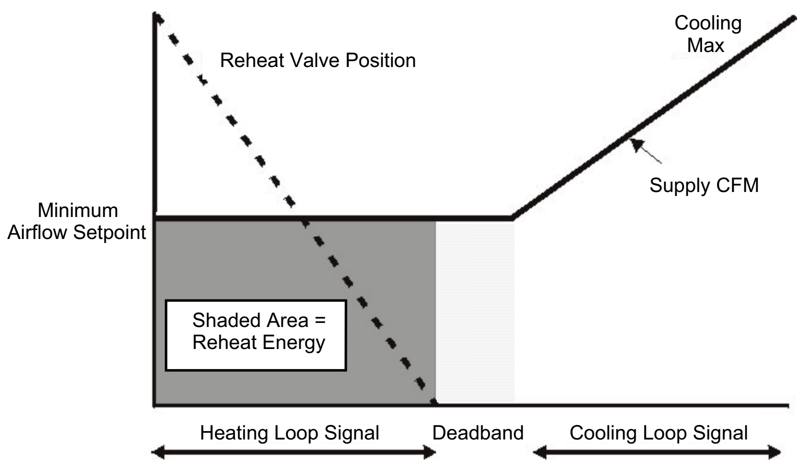

Figure 21. VAV Hot Water Reheat Box Control - Single Maximum

Recommended Approach (Dual Maximum)

A more energy efficient VAV box control logic is the "dual maximum" strategy depicted in Figure 22. In addition to a minimum airflow setpoint and a cooling maximum airflow setpoint, there is also a heating maximum airflow setpoint; hence the name "dual maximum". The heating maximum airflow setpoint is generally equal to the minimum airflow setpoint in the conventional approach described above; in both cases they would be determined based on meeting heating load requirements. That allows the minimum airflow setpoint to be much lower (see "Minimum airflow setpoints").

The control logic of the dual maximum approach is described by the following sequence of operation:

1. When the zone is in the cooling mode, the cooling loop output is mapped to the airflow setpoint from the cooling maximum to the minimum airflow setpoints. The hot water valve is closed.
2. When the zone is in the deadband mode, the airflow setpoint shall be the minimum airflow setpoint. The hot water valve is closed.
3. When the zone is in the heating mode, the heating loop shall maintain space temperature at the heating setpoint as follows:
    a. From 0%-50% loop signal, the heating loop output shall reset the discharge temperature from supply air temperature setpoint (e.g., 55°F) to 90°F. Note the upper temperature is limited to prevent stratification during heating.
    b. From 50%-100% loop signal, the heating loop output shall reset the zone airflow setpoint from the minimum airflow setpoint to the maximum heating airflow setpoint. The supply air discharge temperature remains at 90°F.
4. The hot water valve shall be modulated using a PI control loop to maintain the discharge temperature at setpoint. Note that directly controlling the hot water valve from the zone temperature PI loop is not acceptable since it will not allow supply air temperature to be under control and limited in temperature to prevent stratification.
5. The VAV damper shall be modulated to maintain the measured airflow at setpoint.

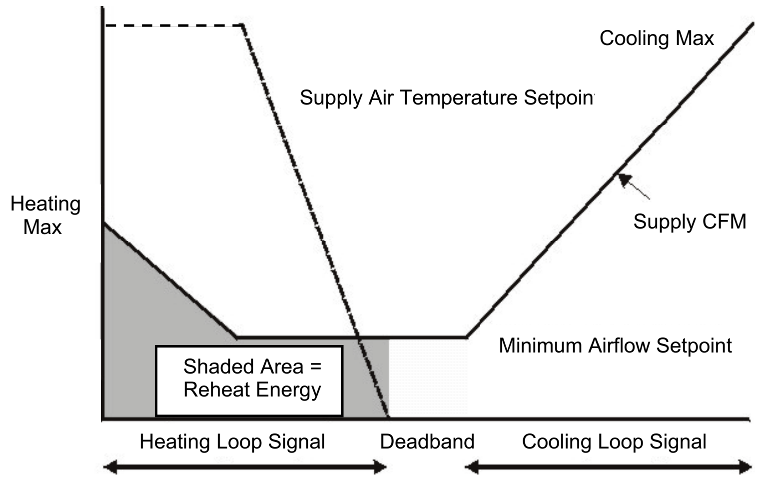

Figure 22. VAV Hot Water Reheat Box – Dual Maximum

While the hatched area (which is proportional to the magnitude of the reheat energy) in

Figure 21 and Figure 22 may not appear to be very different, the difference can be quite significant on an annual basis since VAV boxes typically spend much of their time in the deadband and mild heating modes. For example, suppose a zone has a cooling design maximum of 1.5 CFM/ft^2. With a single maximum VAV box control and a 30% minimum, 0.45 CFM/ft^2 would be supplied in deadband. With a dual maximum VAV box control and a properly selected minimum (see "Minimum airflow setpoints"), this rate could drop to about 0.15 CFM/ft^2. In this case, the single maximum results in three times more airflow and three times more reheat energy than the dual maximum approach in all but the coldest weather.

The arguments supporting the dual maximum approach include:

- It allows for much lower airflow rates in the deadband and first stage of heating while still maintaining code ventilation requirements. This reduces both reheat energy and fan energy.

- By reducing the deadband minimum airflow rate, spaces are not over-cooled when there is no cooling load and "pushed" into the heating mode.

- By controlling the reheat valve to maintain discharge supply temperature rather than space temperature, supply air temperature can be limited so that stratification and short circuiting of supply to return does not occur. This improves heating performance and ventilation effectiveness (see Figure 22). It also keeps the HW valve under control at all times, even during transients such as warm-up. With two-way valves, this makes the system completely self-balancing, obviating the need for balancing valves and associated labor. (See also Taylor, S.T. Balancing Variable Flow Hydronic Systems, " ASHRAE Journal, October 2002.)[24]

Disadvantages include:

- Only a few direct digital control manufacturers that have "burned-in" programming in their controllers (often called "preprogrammed" "configurable" controllers) offer dual maximum logic as a standard option. However, there are many fully programmable zone controllers on the market and all of them can be programmed to use this logic.

- There is a greater airflow turndown and potential risk of dumping and poor air distribution with improperly selected diffusers. See "Minimum airflow setpoints".

- While ventilation codes are met, airflow rates are reduced which results in higher (although acceptable) concentrations of indoor contaminants.

Minimum airflow setpoints

Code Limitations

Title 24 places limits on both the lowest and highest allowable VAV box minimum airflow setpoints.

The lowest allowable setpoints are those required to meet ventilation requirements (see Code Ventilation Requirements). Note that since Title 24 allows air transferred or returned from other ventilated spaces to be used for ventilation, the minimum airflow setpoint need <u>not</u> be adjusted for the fraction of "fresh" air that is in the supply air. In other words, if the minimum ventilation rate is 0.15 cfm/ft^2, then the minimum airflow setpoint may be set to that value even if the supply air is not 100% outdoor air, provided the design minimum outdoor air at the air handler is delivered to some other spaces served by the system (again, see Code Ventilation Requirements).

Title 24 Section 144 limits the highest allowable minimum airflow setpoints in order to minimize reheat energy. In Section 144, the minimum setpoint is mandated to be no greater than the largest of the following:

1. 30% of the peak supply volume; or

[24] In a traditional control sequence, the maximum call for heating would open up the heating valve fully. During warm-up, the coils closest to the pump would likely take more than their design share of the hot water flow, partially starving the coils furthest from the pump. By controlling leaving air temperature instead of valve position each reheat coil is limited to its design flow.

2. The minimum required to meet the ventilation requirements of Section 121; or
3. 0.4 cubic feet per minute (cfm) per square foot of conditioned floor area of the zone; or
4. 300 cfm.

In common practice, VAV box minimums are set much higher than even this code limit, and much higher than they need to be. In the buildings surveyed for this document, the box minimums ranged between 30% and 50% of design airflow (see Table 12). Unfortunately, this common practice significantly increases reheat fan, and cooling energy usage.

Table 12. VAV Box Minimums from Five Measured Sites

Site	Average	Type
#1	No data	
#2	28% +/- 19%	VAV reheat with dual maximums
#3	30%	VAV interior with parallel fan-powered boxes with electric reheat
#4	50%	VAV reheat with single maximum
#5	40%	VAV reheat with single maximum

With the dual maximum strategy (see "Recommended Approach (Dual Maximum)"), the minimum airflow setpoint need not be based on peak heating requirements. To minimize energy usage while still complying with Title 24 ventilation requirements, the minimum airflow setpoint should be set to the greater of:

1. The minimum airflow at which the box can stably control the flow (see "Determining the Box Minimum Airflow"); and
2. Ventilation requirement (see "Code Ventilation Requirements").

Although the dual maximum strategy saves energy, meets the Title 24 Section 144 requirements and maintains code required ventilation, some engineers remain concerned about the following issues:

- Minimum air movement and stuffiness
- Diffuser dumping and poor distribution problems
- Air change effectiveness

These concerns are largely anecdotal and unsupported by research, as shown in the following paragraphs.

Minimum Air Movement and Stuffiness

ASHRAE Standard 55-1992 states clearly that "there is no minimum air speed necessary for thermal comfort" if the other factors that affect comfort (drybulb temperature, humidity, mean radiant temperature, radiant and thermal asymmetry, clothing level, activity level, etc.) are within comfort ranges. People routinely experience this at home: they can be perfectly comfortable with no air movement (windows closed, furnace and AC unit off) yet for some reason many HVAC engineers insist that these same people need air movement at work. They use this to justify higher minimum airflow setpoints (e.g., 0.4 CFM/ft^2, the maximum allowed by Title 24).

There are virtually no studies that support this perception, however. Even if perceptible air motion was associated with comfort, higher airflow rates out of a given diffuser are unlikely to increase perceived air velocities in the occupied region simply because the velocities are below perceptible levels even at full airflow by design — that is, after all, what diffusers are designed and selected to do.

Simply put, studies to date show fairly conclusively that complaints of "stuffiness" and poor air motion are not due to lack of air movement but instead indicate that spaces are too warm. Lower the thermostat (e.g., to <72°F) and the complaints almost always go away.

Dumping and Poor Distribution

Another concern when using a relatively low box minimum is degradation of diffuser performance. There are two potential issues with low minimums: stratification and short-circuiting in heating mode (see discussion of air change effectiveness) and dumping in cooling mode. A diffuser designed for good mixing at design cooling conditions may "dump" at low flow. Dumping means that the air leaving the diffuser does not have sufficient velocity to hug the ceiling (the so-called Coanda effect) and mix with the room air before reaching the occupied portion of the room. Instead, a jet of cold air descends into the occupied space creating draft and cold temperatures which in turn creates discomfort. The industry quantifies diffuser performance with the Air Diffusion Performance Index (ADPI). Maintaining nearly uniform temperatures and low air velocities in a space results in an ADPI of 100. An ADPI of 70 to 80 is considered acceptable. The ASHRAE Handbook of Fundamentals gives ranges of T_{50}/L for various diffuser types that result in various ADPI goals. L is the characteristic room length (e.g., distance from the outlet to the wall or mid-plane between outlets) and T_{50} is the 50 FPM throw, the distance from the outlet at which the supply air velocity drops to 50 feet per minute. For a perforated ceiling diffuser, the Handbook indicates that acceptable ADPI will result when T_{50}/L ranges from 1.0 to 3.4. This basically means that best turndown possible while still maintaining an acceptable ADPI is 1/3.4 = 30% turndown. Other types of diffusers have greater turndown. A light troffer diffuser, for example, can turndown almost to zero and still maintain acceptable ADPI.

Note that ADPI tests are always done under a cooling load. For all diffuser types, the lower the load, the greater the turn-down percentage while still maintaining acceptable ADPI. The lowest load catalogued in the ASHRAE Handbook of Fundamentals is 20 Btu/h/ft^2, equal to roughly 1 cfm/ft^2 which is a fairly high load, well above that required for interior zones and even well shaded or north-facing perimeter zones. To achieve good air distribution when the load is substantial, maintaining diffuser throw is important. However, when the low airflow rates occur with the dual maximum strategy, loads are by definition very low or zero. Under these conditions, acceptable ADPI may occur with even zero airflow. Again, consider experiences in the home: temperatures around the home can be very uniform with no air circulation when AC and heating equipment is off at low or no loads.

Concern about dumping may be overblown (no pun intended). There are many buildings operating comfortably with lower than 30% airflow minimums. Researchers at UC Berkeley and Lawrence Berkeley National Laboratory performed several laboratory experiments with two types of perforated diffusers and two types of linear slot diffusers (Fisk, 1997;

Bauman, 1995). They measured air change effectiveness (using tracer gas) and thermal comfort (using thermal mannequins) in heating and cooling mode and at various flow rates (100%, 50%, and 25% turndown). They also measured throw and space temperature and velocity distribution from which they calculated ADPI. They found that in cooling mode ADPI depended more on the diffuser type than the flow rate. For example, the least expensive perforated diffuser had an ADPI of 81 at 25% flow. They also found that in nearly all cooling tests thermal comfort was within the acceptable range and air change effectiveness was consistently at or above 1.0.

Air Change Effectiveness

Air change effectiveness measures the ability of an air distribution system to deliver ventilation air to the occupied (breathing) zone of a space. A value of 1.0 indicates perfect mixing; the concentration of pollutants is nearly uniform. A value under 1.0 implies some short-circuiting of supply air to the return. Values greater than 1.0 are possible with displacement ventilation systems where the concentration of pollutants in the breathing zone is less than that at the return. Studies have shown that air change effectiveness is primarily a function of supply air temperature, not diffuser design or airflow rates. Measurements by all major research to-date (e.g. Persily and Dols 1991, Persily 1992, Offerman and Int-Hout, 1989) indicate that air change effectiveness is around 1.0 for virtually all ceiling supply/return applications when supply air temperature is lower than room temperature. Bauman et al 1993 concluded that "a ceiling mounted supply and return air distribution system supplying air over the range 0.2 to 1.0 cfm/ft^2 [1.0 to 5.0 L/s·m^2] was able to provide uniform ventilation rates into partitioned work stations. The range of tested supply volumes represented rates that were below and above the [diffuser] manufacturer's minimum levels for acceptable performance." Fisk et al 1995 concluded that "when the supply air was cooled, the [air change effectiveness] ranged from 0.99 to 1.15, adding to existing evidence that short-circuiting is rarely a problem when the building is being cooled." This study was based on air flow rates ranging from 0.2 to 0.5 cfm/ft^2 (1.0 to 2.5 L/s·m^2) using linear slot diffusers as well as two types of inexpensive perforated diffusers.

These studies indicate that low air change effectiveness is only an issue in heating mode; the higher the supply air temperature above the space temperature, the lower the air change effectiveness. This suggests that the low minimum airflow setpoints we propose will result in lower air change effectiveness for a given heating load since the supply air temperature must be higher. But air change effectiveness will stay around 1.0 if the supply air temperature is no higher than about 85°F[25]. With the dual maximum approach with the hot water valve controlled to maintain supply air temperature (rather than directly from room temperature), the supply air temperature can be limited below 85°F, thus mitigating or even eliminating this problem. Note that some zones may require higher supply air temperatures to meet peak heating load requirements. If so, the problem will be the same for both the dual maximum and conventional single maximum approach since at peak heating (the far left side of the control diagram), both have the same airflow setpoint. For these spaces, fan-powered mixing boxes can be used to increase heating airflow rates while at the same time limiting

[25] See ASHRAE Standard 62, Addendum 62n, Table 6.2. 85°F limit assumes 70°F space temperature (15°F ΔT).