Occupancy Based Control Strategy for Variable-Air-Volume (VAV) Terminal Box Systems

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ABSTRACT

The terminal box (TB) is one of the key components in variable-air-volume (VAV) systems. The minimum air flow set point of the VAV TB is an important factor to determining thermal comfort, indoor air quality and energy consumption. The newly developed occupancy based air distribution system control presented in this paper resets the minimum air flow set point for each TB based on the actual occupancy of the space served and ASHRAE ventilation standard. Differentiated from existing motion detection sensors on the market, building occupancy sensors count the number of occupants for each room. Occupancy data of each room, each zone and the whole building are collected and transferred to the building automation system (BAS) in real time using a wireless sensor network. The data are then used to determine the minimum air flow set point. This paper presents the system architecture, control strategy and available sensor technology.

INTRODUCTION

Single duct VAV air-handling units (AHUs) are one of the most popular systems in the USA today. Terminal boxes are critical components of VAV systems. The minimum air flow rate of terminal boxes is a key factor influencing comfort, indoor air quality (IAQ) and energy cost (Cho and Liu 2008, 2009). In the 1980s and 1990s, a flow station was developed and added to the inlet of terminal boxes to provide data for use in controlling the air flow rate through the boxes, using a direct digit controller. Variable-volume pressure-independent terminal boxes have become one of the most popular types of terminal box installed today. The system consists of a controller, a thermostat, an actuator, a damper, a heating coil and a flow station. As the room temperature changes, the flow station controls the damper to maintain the required flow rate within an established range. The required air flow rate normally comes from a control loop seeking to satisfy the zone temperature set point.

For cooling-only VAV terminal boxes, there is no heating coil. Control of the minimum volumetric flow rate is used to ensure that sufficient ventilation air is delivered to the zone served regardless of the thermal load (McDowall 2008). Pressure-independent box controls are preferred over pressure-dependent box controls for many reasons, including that both minimum and maximum air flow rates can be controlled regardless of duct pressure, and flow rates are functions of the available duct pressure. A fixed minimum air flow rate is used in conventional terminal box control sequences, which can cause occupant discomfort or excessive energy use. If the minimum air flow rate is higher than required to meet the zone load, significant simultaneous reheating and cooling may occur, and the AHU will consume more fan power than necessary (Liu and Zhu 1999, Liu 2001, Taylor and Stein 2004). For VAV boxes with reheat, the minimum airflow rate, $V_{\text{min}}$, is typically selected to be the largest of the following (Taylor & Stein 2004):

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• The airflow required to meet the design heating load at a supply air temperature that is not too warm (i.e., not greater than about 90°F/32°C). Warmer temperatures tend to result in poor temperature control due to stratification and short circuiting.

• The airflow required to prevent poor air mixing. This limit depends on the diffuser style and sizing. Thirty percent of the maximum cooling air flow rate \( (V_{\text{max}}) \) is a common rule-of-thumb, but some research (Bauman et al. 1995) has shown that lower rates are satisfactory.

• The minimum air flow rate required for ventilation. Depending on the code one is designing to, determining this rate can be simple (e.g., for California’s Title 24 (CEC 2008)) or it can be complex due to varying supply air rates and outdoor air fractions (e.g., for ANSI/ASHRAE Standard 62 (ASHRAE 2007b)). These three options determine the lowest required value of \( V_{\text{min}} \).

To minimize reheat energy losses, \( V_{\text{min}} \) should not exceed the value specified by energy codes. Both California Title 24 and ASHRAE Standard 90.1 limit \( V_{\text{min}} \) to the largest of:

• 30% of \( V_{\text{max}} \);

• 0.4 cfm/ft² (2 L/s per m²) of conditioned floor area of the zone; and

• 300 cfm (142 L/s).

Common practice uses simple methods to determine the minimum air flow rate through terminal boxes. The high limit of the three maximum values established by code requirements based on ASHRAE Standard 90.1 and California Title 24 are widely implemented in the field. Based on field experience (Cho and Liu 2008, 2009, Liwerant 2008), 30% or more of \( V_{\text{max}} \) is still very commonly used in current HVAC systems. The 0.4 cfm/ft² for the air-conditioned floor area is also undesirable but a commonly selected value. If the zone served by the box has a low heating load but a large area, the calculated air flow rate may be too high based on this approach. Finally, even the value of 300 cfm (the third option) is a problematic value because it was originally derived from calculations for zones requiring special thermal considerations, such as a small zone with a high heating load or a space with north facing glass windows. Unfortunately, some engineers apply 300 cfm as a standard practice for every space, regardless of the thermal conditions (Liwerant 2008).

In many buildings, control vendors or control system integrators are responsible for implementing a large number of terminal boxes with differing load conditions. Time constraints can lead to use of common practices that lead to suboptimal control. Here are some examples of common issues for the conventional minimum air flow setting:

**Case 1:** The minimum air flow set point is much higher than necessary for an interior zone. As a result, the damper of pressure-independent terminal boxes opens more than necessary in order to meet the design minimum flow rate, introducing more cold air than needed into the space even though the zone cooling temperature set point is satisfied. This causes overcooling and occupant discomfort. Under these conditions, some occupants will use foot heaters even during summertime. Furthermore, some occupants try to block the diffuser (e.g., using cardboard) to mitigate the cold draft.

**Case 2:** The reheat valves are opened during the summertime for exterior zone terminal boxes to compensate for a high minimum air flow setting. This causes excessive reheating to compensate for the oversupply of cooling plus greater than necessary fan power consumption.

**Case 3:** The actual building occupancy differs from the assumed design occupancy. For example, a conference room can be used by varying numbers of occupants. It is very common for a conference room with a capacity of 30 people to be used at times for meetings by only 2 or 3 people. Under these conditions, the conference room is very cold because of a high minimum air flow rate is set to meet the ventilation requirements for the design occupancy. No occupancy information is used to control the terminal, resulting in both uncomfortably cold occupants and wasted energy for cooling and fan operation. In fact, the air flow required for design occupancy is often supplied even when conference rooms are unoccupied, when no ventilation is needed because terminal box control does not commonly use even motion sensors to detect the presence and absence of occupants.

**Case 4:** The actual occupancy distribution in office areas changes over time as space uses are changed. For example, an
office might be converted to a storage room or the number of occupants of an open plan office space may vary significantly because a company downsizes or several staff are out of the office traveling. The minimum air flow set point should be adjusted to conform to occupancy changes. Energy is wasted when air is provided at the same flow rate when the office is unoccupied as when it is half occupied or fully occupied.

These issues represent real challenges in the daily operation of a commercial building. Many investigations have explored control strategies for improving the performance of VAV terminal controllers. Stein (2005) suggested the dual-maximum-control sequence in which the air flow set point is reset from maximum to minimum before the set point for supply air temperature is reset from minimum to maximum as the load goes from full cooling to full heating. Liu et al. (2000) developed an operation and control strategy for the terminal boxes with the air flow set point reset to improve building comfort and energy efficiency during the unoccupied and lightly occupied hours. Liu’s method maintains zone temperatures at comfortable levels with daytime set points during unoccupied or lightly occupied hours, which decreases heating energy, cooling energy and fan power use significantly. This practice can be extended to normal operation hours for spaces that are unoccupied or lightly occupied at times by using an appropriate control sequence (Liu 2000).

All of these advanced designs and control methods still do not completely solve the challenges of varying occupancy in commercial building zones with time. The commercial real estate occupancy rate can vary frequently for economic reasons. Occupancy also varies dynamically because of meetings, traveling, staff termination, and office relocation. Energy hogs such as conference rooms, training rooms and auditoriums are not fully occupied all the time, and the minimum air flow set points for these spaces are still maintained for full occupancy no matter whether three people are in the conference room or 30. This results in significant occupant discomfort and energy waste.

Stanke (2010) proposed possible outdoor air (OA) intake reset approaches for multi-zone system air handlers. One of the approaches involves counting the occupants in a zone and solving an equation to find the current outdoor air intake flow set point needed to provide adequate ventilation for the occupants. This approach can be extended to dynamically resetting the set point for the minimum air flow rate for terminal boxes to improve their energy efficiency.

This paper presents a control algorithm for use in real time based on actual occupancy of the zone served by a terminal box and the ventilation it requires. It is distinct from common practice of demand control ventilation (DCV) in that it focuses on control of VAV terminal boxes whereas DCV as usually practiced uses measurements of CO₂ concentrations in zones served by an air handling unit to control the rate at which outdoor air is brought into the air handler. The paper presents the control algorithm, system architecture for minimum air flow reset based on actual zone occupancy, and the current state of technology for occupancy sensing.

DYNAMIC CONTROL STRATEGY

This section presents the improved dynamic control strategy for VAV terminal box control that enables matching of ventilation rates with actual zone occupancy to minimize energy use for cooling, reheating, and fan operation.

Determine cooling minimum air flow rate dynamically

In contrast to other terminal box control algorithms and common practice, the improved control system strategy determines the minimum air flow rate for cooling, using the actual occupancy (i.e., number of occupants) and corresponding ventilation requirement for each zone. In this study, ASHRAE Standard 62.1-2007 is used to establish ventilation requirements. Stanke (2010) proposed an 11-step design-calculation process, which uses equations and concepts first required by Standard 62.1-1989 and subsequently updated by Standard 62.1-2004 and 2007, to determine the required ventilation air flow rate. We use some of these steps in our minimum air flow rate requirement calculation procedure, which follows.

Step 1. ASHRAE Standard 62.1-2007 prescribes minimum fresh air breathing zone ventilation rates and a procedure to find the minimum intake air flow rate needed for different ventilation systems. The design outdoor air flow rate required in the breathing zone of the occupiable space is determined in accordance with Equation (1), which accounts for people-related
indoor contaminant sources (e.g., bioeffluents) and area-related sources (e.g., carpeting and furnishings), as shown in Table 6-1 of ASHRAE Standard 62.1-2007.

\[ V_{bz} = R_p P_z + R_s A_Z, \]  

where

- \( V_{bz} \) is the required volumetric flow rate for outdoor air in the breathing zone, ft³/min (L/s),
- \( R_p \) is the outdoor air flow rate required per person as determined from Table 6-1 of ASHRAE Standard 62-2007, ft³/min-person (L/s-person),
- \( P_z \) is the zone population (largest number of persons expected to occupy the zone during typical use), persons,
- \( R_s \) is the outdoor air flow rate required per unit area as determined from Table 6-1 ASHRAE Standard 62-2007, ft³/min per ft² of floor area (L/s-m²),
- \( A_Z \) is the zone floor area, ft² (m²).

Pre-determined values for the required outdoor air flow rate per person are given by Table 6-1 of ASHRAE Standard 62.1-2007. The zone floor area can be obtained from the as-built architectural drawings. The only parameter unknown in this equation is the actual occupancy number for the zone, which is discussed in the next section. ASHRAE Standard 62.1-2007 permits an HVAC system to “reset the design outdoor air intake flow and/or space or zone air flow as operating conditions change.” The standard cites a third condition that may be used as the basis for dynamic reset control. This condition relates to variations in the fraction of outdoor air in the primary air stream when excess ventilation air is provided during free-cooling with outdoor air (economizer cooling) (Stanke 20006). Therefore, the actual OA intake can be different with time (ASHRAE 2007a).

**Step 2.** Look up the zone air-distribution effectiveness (\( E_z \)) in Table 6-2 of Standard 62.1 (ASHRAE 2007a), based on supply diffuser and return grill locations and the supply air temperature. The effectiveness, \( E_z \), can be a dynamic value; in some zones \( E_z = 1.0 \) when delivering cool air, but it may drop to \( E_z = 0.8 \) when delivering warm air.

**Step 3.** Find the minimum required outdoor air flow rate (\( V_{oa} = V_{bz} / E_z \)) to the zone. This outdoor air flow rate must be delivered to the zone in the supply air stream from the terminal box.

**Step 4.** Find the average outdoor air fraction (\( X_s \) (or OAF) = \( V_{oa} / V_{ps} \)) for the air handler supplying air to the terminal box, i.e., the fraction of outdoor air needed in the primary airstream when all breathing zones need exactly the same outdoor air fraction. In our application, \( X_s \) is the ratio of actual outdoor air intake rate (\( V_{oa} \)) to the total discharge air flow rate (\( V_{ps} \)) for the air handler.

Accurately measuring the rate of outdoor air flow into HVAC systems directly is technically challenging, and typical practices do not always satisfactorily determine minimum ventilation rates (Fisk et al. 2003). An alternative to direct measurement is to determine the outdoor air flow rate as the product of the measured supply air flow rate and the outdoor air fraction (OAF) in the supply air stream, which can be determined from air temperature measurements, a mass balance and an energy balance on the mixing of outdoor air and recirculated air to form mixed air in the air handler, i.e.,

\[ OAF = \text{MIN} \left[ \text{MAX} \left( \frac{MAT - RAT}{OAT - RAT}, \text{Min}_{OAF} \right) , 1 \right] \]  

Here, OAT, RAT and MAT represent the temperatures of the outdoor air, return air and mixed air, respectively, RAF is the return air fraction, and Min_{OAF} is the OAF corresponding to the minimum outdoor air intake rate. The minimization of the bracketed quantity ensures that values greater than 1.0 that may result from measurement uncertainty when OAT=RAT are not used, and the maximization is to ensure that erroneous values calculated from measurements when the value of MAT is very close to the value of RAT are not used but rather the value of Min_{OAF}, which corresponds to the specified minimum outdoor air-flow rate, is used.
Non-uniform airstream temperatures and small differences between the measured air temperatures can cause large errors in the calculated OAF and associated outdoor air flow rate (Krarti et al. 1999). The error in the calculated OAF can be large when the OAT is closed to RAT (i.e., as the difference OAT-RAT approaches zero).

Another method for determining the OAF uses measurements of CO₂ concentrations in the air streams. Krarti et al. (1999) recommended using a CO₂ mass balance to determine the OAF. In terms of CO₂ concentrations in the outdoor, return, mixed and supply airstreams ($X_{OA}$, $X_{RA}$, $X_{MA}$ and $X_{SA}$, respectively), the OAF can be expressed as

$$OAF = \frac{X_{MA} - X_{RA}}{X_{OA} - X_{RA}} \approx \frac{X_{SA} - X_{RA}}{X_{OA} - X_{RA}}. \quad (3)$$

**Step 5.** Find the terminal box minimum required air flow. If the OAF is known, the minimum air flow set point can be determined from the following equation:

$$V_{min} = \frac{V_{oz}}{OAF}. \quad (4)$$

Equation (4) is based on the assumption that the outdoor air and return air are well mixed in the air handler.

**Improved Terminal Box Control Logic**

The improved dynamic control algorithm for VAV terminal units will maintain the zone thermal comfort and meet ventilation requirements by using continuously monitored values of the zone temperature and occupancy to determine the minimum required air flow rate. The control logic involves the following:

- The terminal box damper is modulated to maintain the zone temperature at its set point and to provide the flow rate necessary to meet the outdoor air ventilation requirements of the people actually in the zone (i.e., actual occupancy).
- During terminal box cooling mode, the cooling minimum air flow rate is reset based on the actual occupancy of the zone served and ASHRAE standard 62.1 every 5 minutes (or some other value suitably short time but not so short as to cause damper hunting when people enter and leave the zone for a short time).
- During terminal box heating mode (VAV with reheat terminal box only), the heating minimum air flow rate is selected as the maximum of following values: 1) the minimum air flow rate required to meet the ventilation needs based on actual occupancy and the ASHRAE Standard 62.1 requirement for the zone and 2) the minimum air flow rate required to prevent air stratification in the zone and/or short-circuiting.
- If there are no occupants in the served zone, the minimum air flow set point is reset to zero. The terminal unit is operated to maintain the zone temperature set point only.

**SYSTEM ARCHITECTURE AND COMPONENTS**

The proposed system consists of building occupancy sensors, a sensor network, a signal processing system, a building automation system (BAS), a building automation control network, and VAV terminal units with controllers as shown in Figure 1.

- Building occupancy sensors: These can be CO₂ sensors, passive infrared (PIR) sensors, video sensors, ultra-sonic sensors, badge counters or any other people counting sensors and are required in each room to count occupancy.
Sensor network: A wired or wireless sensor network can be used in this system. It can be Ethernet local area network (LAN) with BACnet communication protocol. For wireless communication, it can be the IEEE 802.15.4 protocol (IEEE 2003) with ZigBee, a low-cost, low-power, wireless mesh networking standard (Zigbee Standards Organization 2008).

Signal processing circuit: This includes occupancy sensor data aggregation and processing, such as data noise removal, statistical distribution in each room, daily change trend, etc. The sensor processing circuit includes the noise filter, amplifier, multiplexer and A/D converter.

Building automation system: a computerized, intelligent network of electronic devices, designed to monitor and control the mechanical and lighting systems in a building.

Building automation control network: communication protocol such as BACnet or LonWorks.

Terminal unit and controller: This can be a single duct VAV terminal unit, fan power box or dual duct terminal unit.

The building occupancy sensors count the occupancy for all rooms and deliver the measured data to the signal processing station through the sensor network. After the signal processes, the actual occupancy (i.e., number of people) for each room is delivered to the building automation system. A protocol converter or gateway may be needed between the BAS and network. The building automation system then can sum the occupancies of the rooms in each zone to determine the occupancy of each zone. Based on the actual zone occupancy, the minimum air flow rate can be reset following the procedure described in the DYNAMIC CONTROL STRATEGY section.

The building occupancy sensor is the key to this new control method. Many situations exist where it is useful or essential to count people, and numerous automated people-counting systems have been developed over the years. Several kinds of counters that require contact with people, such as turnstiles, are used because contact-type counters count very accurately. These counters, however, cannot be applied to spaces within commercial buildings because, except at a few critical places (e.g., entrances), they obstruct the normal flow of people in work spaces and would require installation for each room. Mat-type switches, another type of contact counter, are insufficiently durable to withstand repetitive foot stresses (Hasinmoto et al. 1997a and 1997b, Yoshiike et al. 1999, Yoshinaga et al. 2009).

Most commercially available non-contact-based counters use infrared beams or ultrasonic sensors. Other specialized human information sensors have also been developed for counting occupants (Amin et al. 2008). Several kinds of sensors currently can provide information on occupancy, such as video cameras equipped with people-counting software, optical tripwires and pyroelectric infrared (PIR) motion sensors that count the number of people crossing a particular area, and sensors that measure the concentration of CO2. Brief discussions of available technologies follow.

- CO2 sensors provide concentration readings in parts per million (ppm), which are indicative of the occupancy of a

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**Figure 1** Occupancy Based Terminal Box Control Diagram
space. However, reliably correlating CO₂ levels with actual occupancy is difficult because of the high variability of readings and slow response time of CO₂ sensors. Variability arises from fluctuations in ambient CO₂ levels, HVAC system settings, and the opening/closing of doors. Furthermore, CO₂ measurements suffer from slow response time (Meyn et al. 2009). For example, the inevitable delay in CO₂ concentration increase following an increase in occupancy is at least 10 to 20 minutes.

- PIR detectors provide indications of motion within the sensor range. By using them in pairs, PIR detectors can be used to determine the direction of motion, e.g., a person entering or leaving a room through a doorway. PIR detectors, however, have limitations for this application. First, the sensor range is limited, and individual PIR sensors are not good for monitoring large spaces. Second, multiple people passing a PIR sensor (e.g., in a doorway) at the same time may be undercounted.

- Video cameras can provide information regarding people count and the direction of flow. These cameras if not properly installed and configured, can exhibit significant errors, arising from three main factors. First, video sensors are affected by lighting conditions. Low light levels can lead to single persons being counted multiple times. Also, turning a light switch on or off may trigger a sensor count. Second, multiple people crossing the field of view at the same time may be undercounted. Last, the video system may count several crossings at times when occupants loiter in the camera’s field of view. Such events can lead to a significant positive bias.

- Smart camera object position estimation system (SCOPES): Kamthe et al. (2009) developed the SCOPES system, a wireless camera sensor network for gathering traces of human mobility patterns in buildings. The claimed accuracy is 80% of events counted correctly. A disadvantage with visual counting systems is their high cost. Other critical drawbacks include poor accuracy caused by difficulty in recognizing occupants whose clothing color is close to the background color and ambient lighting interference (Hasinmoto et al. 1997a and 1997b, Yoshiike et al. 1999, Yoshinaga et al. 2010). SCOPES also has a shorter lifetime and higher power consumption than thermal imaging systems.

- Thermal image systems using thermal array detectors: Hashimoto et al. (1996, 1997a, 1997b, 1998, 2000) developed a people-counting system that consists of a one-dimensional eight-element array detector made from pyroelectric PbTiO₃ ceramics, an infrared (IR) transparent spherical lens and a cylindrical mechanical chopper. This compact sensor is set at the top of a doorway with the element array parallel to the direction of movement of people through the doorway. The sensor, mounted on the ceiling detects infrared radiation from the floor except when people pass through the doorway, changing the radiation incident of the detector and the signal output from the detector elements. Thus, the number of people passing in each direction through the doorway can be obtained by processing the detector output. This system can detect the net flow of people through a 1-meter wide doorway (2.2-meter height) with more than 98% accuracy (Hashimoto et al. 1996, 1997). The number of people passing by a 2-meter wide door can be detected with more than 95% accuracy (Hashimoto et al. 1998). Errors are caused by large movements of the arms or legs (e.g., gesturing). The detection accuracy can be improved by higher sensor spatial resolution (e.g., by adding elements to the sensor) and better matching the area viewed to individual sensor elements.

- A human information sensor with an umbrella-shaped chopper and an array detector made from pyroelectric ceramic was developed by Yoshiike (1999). A rotating array detector mechanism allows the sensors to have wide views (10-m diameters). With the human detection algorithm, data on occupancy can be detected with 97% accuracy (in 389 samples).

- Amin et al. (2008) developed a system for counting people in a scene using a combination of low-cost, low-resolution visual and infrared cameras. The results of 18 experiments show that the system can be accurate to within 3% over a wide range of lighting conditions.

CONCLUSIONS

A VAV terminal box control strategy based on time varying occupancy of building zones has been presented. The
strategy aims to match the ventilation provided to a zone to the ventilation needs of the occupants actually in a zone at any
time. Occupancy of zones can vary considerably with time. For example, conference rooms can have highly varying
occupancy over the course of a day. At times, they may be fully occupied (at the design occupancy), but at other times
occupancy may be only a fraction of the design value, or the room may be completely unoccupied (with no ventilation being
required). The proposed control strategy adjusts the flow rate through each terminal box based on the actual number of
occupants in the zone served. This approach to control helps minimize fan power consumption and potential simultaneous
heating and cooling.

Key to the proposed control methodology is a technology for sensing the actual occupancy of the zone served in real
time. Several technologies show promise, but none currently fully meets the need at adequate accuracy and sufficiently low
cost.

The authors plan to analyze the potential energy and cost savings from application of the control approach presented in
this paper compared to use of conventional and other advanced control strategies (including CO₂-based demand control
ventilation) for VAV terminal boxes in future work. Furthermore, they plan to investigate advances in occupancy sensing
technologies and ways to potentially adapt existing technologies to meet this sensor need of the occupancy-based control
strategy.

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NOMENCLATURE

\[\begin{align*}
E_z &= \text{Effectiveness} \\
MA &= \text{Mixed air} \\
MAT &= \text{Mixed air temperature} \\
OA &= \text{Outdoor air} \\
OAF &= \text{Outdoor air fraction} \\
OAT &= \text{Outdoor air temperature} \\
RA &= \text{Return air} \\
RAT &= \text{Return air temperature} \\
V &= \text{Air flow rate} \\
V_{\text{min}} &= \text{Minimum air flow rate} \\
V_{\text{max}} &= \text{Maximum air flow rate} \\
X_s &= \text{OA intake ratio}
\end{align*}\]

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