Improving Control of Dual-Duct Single-Fan Variable Air Volume Systems

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ABSTRACT

This paper discusses improved control strategies for dual-duct single-fan variable air volume (VAV) systems. Common control strategy for supply air volume modulation is evaluated, and an improved air volume control strategy that maintains separate cold and hot air duct static pressure set points is presented. The paper also explores the interactions between the cold and hot deck temperatures and duct static pressures, and discusses the impact of non-ideal deck temperature settings on duct static pressures and overall system energy consumption. To compensate the negative impact of non-ideal cold and hot deck temperature set points, the authors propose using real-time duct static pressure readings as feedback signals to fine-tune the deck temperature set points. These new control schemes can reduce simultaneous cooling and heating while reducing fan power consumption.

INTRODUCTION

Dual-duct VAV systems, when properly designed, can be both cost effective and cost efficient as compared with single-duct VAV systems (Kettler 1987). There are two basic types of dual-duct VAV systems – the dual-duct, dual-fan VAV system and the dual-duct, single-fan VAV system. For a dual-duct, dual-fan VAV system, it is possible to maintain two separate duct static pressure set points for supply air volume control – one for the cold air duct and one for the hot air duct (Wendes 1991), therefore achieving higher system efficiency. For a dual-duct, single-fan VAV system, typical supply air volume control strategy is to maintain the lower of the cold and hot air duct static pressures at a preset level, while maintaining the cold and hot deck temperatures at their respective set points (Liu et. al 1997).

Generally, the cold and hot deck temperature set points are reset based on the outside air temperature (Haines 1987; Linford 1987). Liu and Claridge (1998) demonstrated that by optimizing the cold and hot deck temperature reset schedules for a typical dual-duct VAV system, the energy cost can be reduced by 8-20%, depending on the minimum air flow requirements of the terminal VAV boxes. To further increase system efficiency, the duct static pressure set point can be reset based on the load on the air handling unit (AHU) (Liu et. al 1997; Zhu et. al 1998).

Although the cold and hot deck temperature resets can result in energy savings, they may have negative impacts on the duct static pressures and even lead to increased fan power consumption. With cold and hot deck temperature resets, the cold deck temperature set point increases as the cooling load decreases while the hot deck temperature set point increases as the heating load increases. Cooling and heating energy savings will occur as a result of smaller mixing losses at the terminal boxes. However, as the cold deck temperature increases as a result of reset, the required amount of cold air flow may increase if a significant number of terminal boxes are in the cooling only mode (i.e., no mixing occurring). Similarly, the required amount of hot air flow may increase, as the hot deck temperature decreases as a result of the reset. Therefore, the deck temperature resets normally lead to increased cold and hot air flow requirements and hence increased fan power consumption.

To identify the optimal cold and hot deck temperature reset schedules that give the lowest overall thermal and electrical energy consumption, engineers often resort to sophisticated simulation tools (Mutammara and Hittle 1990; Liu and Claridge 1998). Our field experiences indicate that, in general, the reset schedules obtained through such simulation tools offer a good starting point. However, they are not always the optimal reset schedules due to various factors such as the dynamic nature of system load variations, as well as the errors introduced by system simplification, and incorrect assumptions made in the simulation process, etc. One obvious symptom of such a non-optimal reset schedule is the existence of dramatically different duct static pressures among the cold and hot air ducts at different load conditions. This paper evaluates the popular supply air volume control strategy for a dual-duct single-fan system, and provides an improved control scheme. The authors also present a method for fine-tuning the cold and hot deck temperature set points by using real-time feedback signals from the cold and hot duct static pressure sensors.

STATIC PRESSURE CONTROL

In dual-duct single-fan VAV systems, there are two static pressure sensors located in the main supply air ducts – one in the cold air duct and one in the hot air duct, for supply air volume control. In case of a dual-duct triple-deck system, where there are two cold air ducts and one hot air duct, there is one additional cold air duct static pressure sensor.

The most common supply air volume control method is to maintain the lowest of the two or three hot and cold air duct static pressures at a preset level by modulating the supply air fan, through either a variable frequency drive (VFD) or inlet guide vanes, therefore satisfying both the heating and cooling requirements at the terminal boxes. This control strategy is simple and can easily be implemented in a direct digital control (DDC) system. It is perfect if the minimum cold and hot air duct static pressure requirements are the same or very close over the whole range of operating conditions. However, this is rarely the case.

The minimum duct static pressure requirements for the cold and hot air ducts depend on a number of factors, such as the duct length and size, space load conditions, minimum air flow rate requirements, type of terminal box, the temperature set points of the cold and hot decks, etc. Over the entire range of the load conditions, the minimum required cold and hot duct static pressures are usually different. For example, the cold air duct may require a minimum of 1.2 in. wc. static pressure while the hot air duct may require a minimum of 1.0 in. wc. static pressure. Using the control strategy that maintains the minimum of the two static pressures at a preset level, the minimum static pressure set point will be 1.2 in. wc. in order to satisfy both ducts under all conditions. However, there may be situations during the peak heating load periods where the hot air duct is experiencing the lower duct static pressure. For example, the hot air duct static pressure is 0.2 in. wc. lower than the cold air duct static pressure. Under this control strategy, the hot deck will be maintained at 1.2 in. wc. Meanwhile, the cold deck static pressure will be at 1.4 in. wc., which is higher than its minimum required value of 1.2 in. wc. Therefore, both duct static pressures are 0.2 in. wc. above the required level under this circumstance, resulting in a waste of fan power.

An obvious improvement to this popular control strategy is to maintain *separate* minimum duct static pressures for the cold and hot air ducts. In other words, the duct that is experiencing the lower static pressure reading may not necessarily control the supply air volume. To implement this control strategy for a dual-duct single-fan VAV system, two separate PID (proportional, integral, and derivative) control loops are required – one for the cold air duct and one for the hot air duct. The maximum of these two PID control loop outputs, called the lead PID, will be sent to the fan volume control device such as the VFD or the inlet guide vanes. In case of a dual-duct triple-deck VAV system, there will be three PID loops and the highest output will be selected to control the supply air fan.

One obvious concern with this improved control strategy is the PID control loop output windup for the duct or ducts that are not in control of the supply air fan volume. For these ducts, the PID loop outputs (called the lag PIDs) will go to zero after the duct static pressure stays above their set points for an extended period of time (usually several minutes, depending on the proportional band, the integral gain, and the derivative gain of the PID controller). However, this is not a problem. As soon as the duct static pressure drops towards the set point, either due to load changes or the result of the lead PID output being too low, the lag PID output for that duct will start to increase. When the lag PID output surpasses the lead PID output, it becomes the lead PID and assumes the supply air fan volume control, allowing a smooth transition of the supply air fan volume control signal.

FINE-TUNE THE DECK TEMPERATURE SET POINTS

As discussed earlier, for a given system with fixed duct length and size, known terminal box type, and minimum air flow rate requirements, the minimum duct static pressure required depends not only on space load conditions, but also on the cold and hot deck temperature set points. The lower the cold deck temperature, the lower the cold air duct static pressure required. Similarly, the higher the hot deck temperature, the lower the hot air duct static pressure required. Therefore, if the hot and cold deck temperature set points are not appropriate, this can lead to drastically different cold and hot duct static pressure requirements. The duct that requires the highest fan output to maintain its static pressure basically determines the supply air fan speed or inlet guide vanes position.

Figure 1 illustrates such an example. The graph shows the 15-minute trend data from a dual-duct triple-deck VAV AHU during a typical summer day. The supply air fan VFD is modulated to maintain the minimum of the three duct static pressures at the set point, which is reset based on the outside air temperature from 1.2 to 1.4 in. wc. as the outside air temperature changes from 75°F to 95°F. The trend data shows that the duct static pressure (DSP) of the interior cold duct (ICD) is much lower than that of the exterior cold duct (ECD) and the hot air duct. Therefore, the interior cold duct static pressure is controlling the fan speed. While the minimum duct static pressure requirement for the hot duct is only 1.0 in. wc under the same ambient temperature range, the fan speed will still be dictated by the interior cold duct static pressure. This will be true even if the fan speed is modulated using the improved control strategy that maintains separate static pressure set points for the three ducts.

The graph suggests that the two cold deck temperature set point schedules may need to be fine-tuned to help close the gap between the two duct static pressures. Field investigation reveals that, although the interior and exterior cold deck temperatures during this time period were maintained at 56°F, actual interior cold deck temperature was a few degrees higher than that of the exterior cold deck temperature due to bad sensor locations. If the interior cold deck temperature can be decreased by a certain amount, the terminal boxes in the interior area will respond by modulating the dampers towards the closed position on the cold air side. This will increase the interior cold duct static pressure, and eventually slow down the supply air fan speed, therefore saving fan power energy while delivering the same amount of cooling. As the fan speed slows down, the static pressures of the exterior cold air duct and the hot air duct will also decrease.

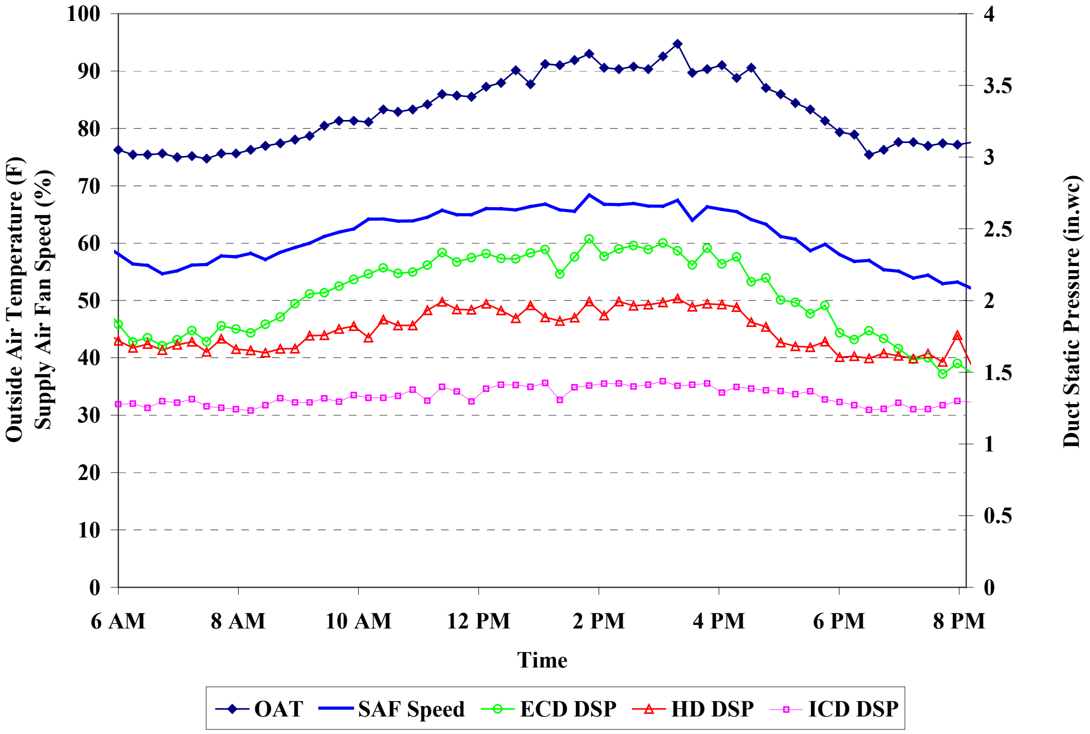

Figure 1. Trend data for a dual-duct triple-deck VAV system

The above example demonstrates that the real-time feedback signal (duct static pressure) can be used to fine-tune the deck temperature set points, therefore compensating for any non-ideal deck temperature reset schedules as a result of either modeling limitation/error or sensor faults.

Resetting the deck temperatures will impact not only the duct static pressures, but also the thermal energy consumption. Hence it is important to know when to apply this real-time feedback reset strategy. To understand, it is helpful to discuss how a dual-duct VAV box works. Figure 2 shows the cold and hot air flow patterns for a typical dual-duct VAV terminal box. At peak cooling load conditions, the VAV box supplies 100% cooling air flow. As the space cooling load decreases, the VAV box reduces the cold air flow until it reaches a minimum point, for example, 30% of maximum cooling air flow. Starting from that point, the hot air damper gradually opens up to maintain the minimum air flow as the cold air flow continues to drop. After the cold air damper closes completely (0% cooling load and 30% heating load) and the heating load continues to increase, the VAV box further opens up the hot air damper until it is fully open.

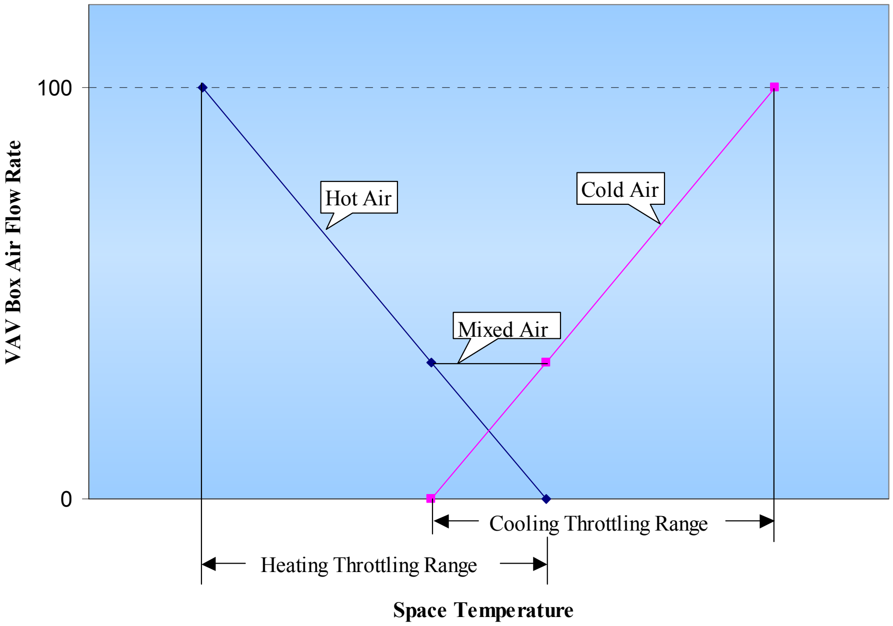

Figure 2. A typical dual-duct VAV terminal box air flow pattern.

Resetting the cold deck temperature higher during mild conditions saves energy if there is cold and hot air mixing at the terminal boxes. However, if a number of boxes are still in the cooling only mode, that is, their cooling air flow rates are greater than the minimum box air flow rates, then the required cold air flow will have to increase after the cold deck temperature is reset higher in order to satisfy those boxes. This results in increased fan power consumption if the cold deck becomes the driving force for the fan speed control.

The following procedure is proposed to be used to improve the cold and hot deck temperature reset schedules using real-time static pressure feedback signals, assuming that the unit is controlled by a DDC system, the supply fan is equipped with a VFD and the fan speed is modulated by maintaining separate duct static pressure set points:

1) Develop and implement the “optimal” duct static pressure set points and cold and hot deck temperature reset schedules through model simulation, coupled with field tests and measurements;

2) Apply real-time cold deck temperature set point adjustment by decreasing the set point if the cold deck static pressure is controlling the fan speed, and the average VAV box cooling load is above the minimum box flow set point (e.g., 30%);

3) Increase the cold deck temperature set point if the cold deck static pressure is not controlling the fan speed (meaning it is well above the set point), and the average VAV box cooling load is below the minimum box flow set point (e.g., 30%);

4) Apply real-time hot deck temperature set point adjustment by increasing the set point if the hot deck static pressure is controlling the fan speed, and the average VAV box heating load is above the minimum box flow set point (e.g., 30%);
5) Decreasing the hot deck temperature set point if the hot deck static pressure is not controlling the fan speed (meaning it is well above the set point), and the average VAV box heating load is below the minimum box flow set point (e.g., 30%).

SUMMARY AND DISCUSSION

This paper evaluated the existing control strategies of cold and hot air duct static pressures and temperatures for a dual-duct single-fan VAV system. It is shown that maintaining the minimum of the cold and hot duct static pressures at a preset level works fine as long as the cold and hot air duct minimum static pressure requirements are very close to each other. However, this is seldom the case and the existing control strategy can lead to increased fan power consumption. An improved control strategy is to maintain *separate* cold and hot air duct static pressure set points. The authors also discussed the interactions between the deck temperatures and duct static pressures, and the impact of deck temperature set points on overall system energy consumption. Although the temperature and static pressure reset schedules are usually developed via sophisticated simulation tools, the schedules are inevitably sub-optimal due to various reasons such as inaccurate assumptions made or sensor faults. To compensate for these errors, the authors proposed the use of real-time duct static pressure readings as feedback signals to fine-tune the deck temperature set points. This will decrease simultaneous cooling and heating energy consumption while reducing fan power consumption.

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