Terminal Box Airflow Reset: An Effective Operation and Control Strategy for Comfort Improvement and Energy Conservation

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ABSTRACT

A new terminal box operation and control strategy, airflow reset, is developed to improve building comfort and energy efficiency during unoccupied and lightly occupied hours. The airflow reset lowers the minimum airflow possibility to zero for variable air volume (VAV) terminal boxes, and changes the airflow to a lower value for constant air volume terminal boxes (CV). It maintains zone temperatures at comfortable levels or daytime set points during unoccupied or lightly occupied hours. It decreases heating, cooling, and fan power significantly. A case study measured 40% of the design airflow reduction in the Air Handling Unit level. This paper presents airflow reset strategies, potential heating and cooling energy savings models, and implementation issues.

INTRODUCTION

During unoccupied hours, the nighttime reset [ASHRAE, 1999] increases the cooling temperature set point to a higher value (30°C/85°F) and decreases the heating temperature set point to a lower value (18°C/65°F). When the zone sensible load ratio is higher than the minimum airflow ratio, the terminal box may provide less airflow to the zone. Consequently, terminal box may consume less heating, cooling, and fan power. If the zone sensible load ratio is lower than the minimum airflow ratio, the terminal box provides the minimum airflow to the zone. No energy savings can be achieved. Since the zone sensible load ratio is less than the minimum airflow ratio most the times for typical commercial buildings, the nighttime reset often achieves no or little energy savings.

The implementation of the nighttime reset is difficult when a building is lightly occupied during non-office hours since both the number of occupants and the number of rooms, which may be used during the weekend or nights, are also unpredictable.

If the nighttime reset is implemented, a pre-cool or a pre-warm period is required to condition room air temperatures to comfortable levels before the office hours. The length of the pre-cool or the pre-warm depends on building thermal energy build-ups and HVAC system capacities. Many HVAC systems have to run 24 hours per day during the summer due to lacking the capacity for pre-cool and significant thermal energy built-up in the building mass. Since the HVAC systems have to eventually remove the thermal energy built-ups, the energy savings of using nighttime reset is very small for large commercial buildings.

The nighttime reset often creates unexpected high electrical power during the pre-cool or the pre-warm period. This can be a problem for some facilities where the pre-cool or pre-warm occurs during the peak demand period.

All these problems can be solved using the airflow reset, which decreases the minimum airflow to a lower value for variable air volume terminal boxes, and reduce the total airflow to a lower value for constant air volume terminal boxes during unoccupied hours. Authors have implemented the airflow reset in dual duct variable air volume terminal boxes [Abbas and Liu, 1996], in dual duct constant air volume terminal boxes [Liu and Zhu, 1998], and in single duct terminal boxes [Zhu et. al, 2000]. This paper presents schedules of airflow reset for typical terminal boxes, models of potential energy savings, and issues of implementation

AIRFLOW RESET

The value of airflow reset depends on terminal box types, zone maximum sensible load ratios, and other parameters. In this study, the airflow is referred to the ratio of the airflow rate to the design airflow rate. The zone sensible cooling load is referred to the ratio of the zone cooling load to the zone design sensible cooling load. The energy consumption is referred to the ratio of the energy consumption to the design sensible cooling load. The energy savings is referred to the ratio of energy savings to the design sensible cooling load. The design sensible cooling load is 14 kJ/kg (6 Btu/lbm) if the supply air and the room air temperatures are 13°C (55°F) and 24°C (75°F), respectively.

Single Duct Constant Air Volume Terminal Box

Figure 1 presents the airflow reset schedule for single duct constant air volume terminal boxes. The airflow reset uses the daytime schedule during the occupied hours and uses the nighttime schedule during unoccupied hours. The standard schedule uses the daytime schedule all the times.

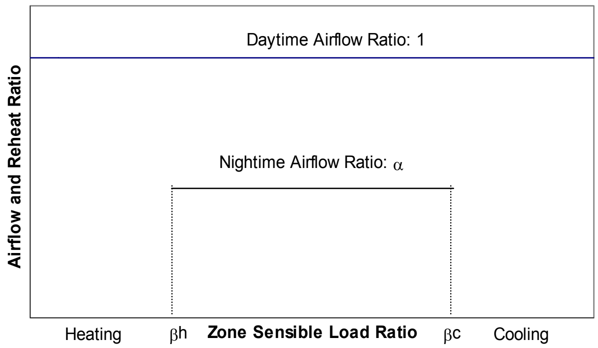

Figure 1: Airflow Reset Schedule for Single Duct Constant Air Volume Terminal Boxes

For the given nighttime airflow ratio α, the zone sensible load ratio must be less than βc and higher than β_h in order to be able to maintain room temperature set point.

$$\beta_c = \alpha \frac{t_r - t_c}{t_r - t_{c,d}} \tag{1}$$

$$\beta_h = \alpha \frac{t_r - t_h}{t_r - t_{c,d}} \tag{2}$$

When the zone load ratio is less than β_c, the terminal box provides α fraction of the design airflow to the zone. Consequently, the zone consumes less reheat, cooling, and fan power. If both the mixed and supply air conditions are the same for both the airflow reset and the standard schedules, the potential reheat and cooling energy savings can be determined using Equations 3 and 4.

$$\eta_{rh} = (1-\alpha)\frac{t_r - t_c}{t_r - t_{c,d}} \tag{3}$$

$$\eta_c = (1-\alpha)\frac{h_m - h_c}{c_p (t_r - t_{c,d})} \tag{4}$$

The potential energy savings depend on the nighttime airflow ratio and the supply air conditions. Figure 2 presents the energy savings ratios versus the reset airflow ratio under the following conditions: (1) the supply air and room air conditions are same as the design conditions; (2) the mixed air enthalpy is same as the room air enthalpy. If the airflow ratio is 0.4, the potential thermal energy savings ratio is 1.35, which includes 0.6 for reheat and 0.75 for cooling.

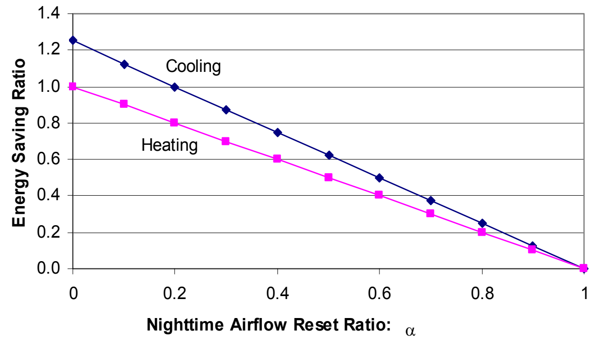

Figure 2: Potential Reheat and Cooling Energy Saving Ratios Versus the Nighttime Airflow Reset Value for Single Duct Constant Air Volume Terminal Boxes

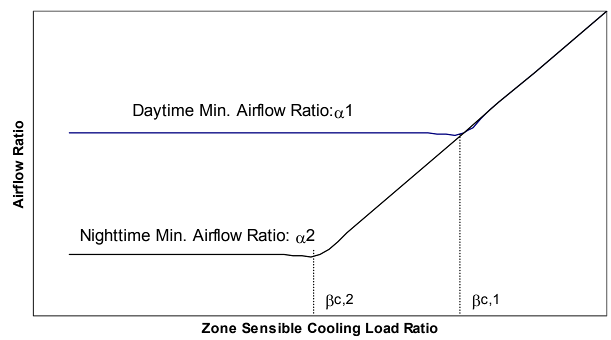

Figure 3: Air Flow Reset Schedules for Single Duct Variable Air Volume Terminal Boxes

Single Duct Variable Air Volume Terminal Box

Figure 3 presents the airflow reset schedule for single duct variable air volume terminal boxes. The daytime schedule has a minimum airflow ratio of α_1. The nighttime schedule has a minimum airflow ratio of α_2. During unoccupied hours, the airflow reset uses the nighttime schedule. During occupied hours, the airflow reset uses the daytime schedule. The standard schedule uses the daytime schedule all the times.

$$\eta_{rh} = \begin{cases} \beta_{c,1} - \beta & \beta_{c,2} \le \beta \le \beta_{c,1} \\ \beta_{c,1} - \beta_{c,2} & \beta \prec \beta_{c,2} \end{cases} \tag{5}$$

$$\eta_c = \begin{cases} (\beta_{c,1} - \beta)\dfrac{h_m - h_c}{C_p(t_r - t_{c,d})} & \beta_{c,2} \le \beta \le \beta_{c,1} \\ (\beta_{c,1} - \beta_{c,2})\dfrac{h_m - h_c}{C_p(t_r - t_{c,d})} & \beta \le \beta_{c,2} \end{cases} \tag{6}$$

Where:

$$\beta_{c,1} = \alpha_1 \frac{t_r - t_c}{t_r - t_{c,d}} \tag{7}$$

$$\beta_{c,2} = \alpha_2 \frac{t_r - t_c}{t_r - t_{c,d}} \tag{8}$$

The potential energy savings depend on the zone load ratio, the supply air conditions (temperature and enthalpy), and $\beta_{c,1}$ and $\beta_{c,2}$, which are functions of the minimum airflow ratio of α_1 and α_2. Figures 4 presents the potential reheat and cooling energy savings ratios versus the zone load ratio under the following conditions: (1) the cold air conditions are same as the design values; (2) the mixed air conditions are the same of the room air conditions; and (3) the minimum airflow ratios are 0.5 for α_2 and 0.1 for α_1. When the zone load ratio decreases from 0.5 to 0.1, the energy saving ratio increases from 0 to 0.5 for cooling and from 0 to 0.4 for reheat.

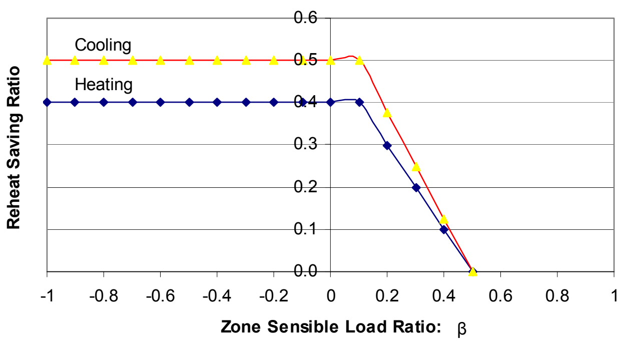

Figure 5: Potential Energy Savings Ratio Versus the Zone Load Ratio for Single Duct Variable Air Volume Terminal Boxes

The airflow reset can also be implemented in single duct variable air volume terminal boxes where reheat coils are not present. In this case, the airflow reset will improve the room comfort and reduce the cooling energy consumption. No reheat savings will be achieved. If reheat coils are installed in the boxes, the airflow reset can save both cooling and heating consumptions.

Dual Duct Constant Air Volume Terminal Box

Figure 6 presents the airflow reset schedule for dual duct constant air volume terminal boxes. During occupied hours, the airflow reset uses the daytime schedule. During unoccupied hours, the airflow reset uses the nighttime airflow schedule. The standard schedule uses daytime schedule all the times. The airflow reset may not be able to maintain room temperature set point provided the zone load ratio is between β_c and β_h.

$$\beta_c = \alpha \frac{t_r - t_c}{t_r - t_{c,d}} \tag{9}$$

$$\beta_h = \alpha_2 \frac{t_r - t_h}{t_r - t_{c,d}} \tag{10}$$

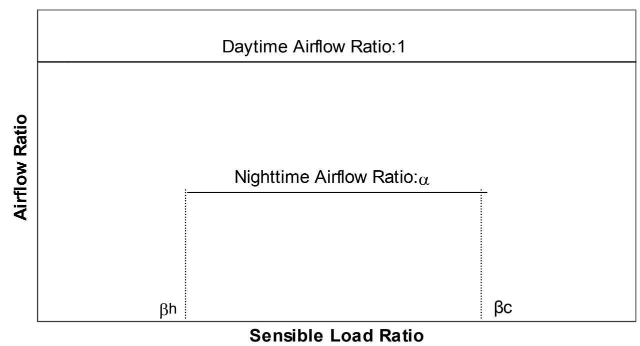

Figure 6: Airflow Reset Schedules for Dual Duct Constant Air Volume Terminal Boxes

When the zone load ratio is between β_c and β_h, the terminal box provides α fraction of design airflow to the zone using the airflow reset schedule. Consequently, the zone consumes less heating, cooling, and fan power than using the standard schedule. The potential energy savings can be calculated using Equations 11 and 12 if both schedules have the same mixed and supply air conditions.

$$\eta_h = \frac{\beta_c \beta_h}{\beta_c - \beta_h} \frac{\alpha - 1}{\alpha} \frac{t_h - t_m}{t_h - t_r} \tag{11}$$

$$\eta_c = \frac{(\alpha - 1)\beta_h}{\beta_c - \beta_h} \frac{h_m - h_c}{C_p(t_r - t_{c,d})} \tag{12}$$

The potential energy savings depend on the reset airflow ratio and the mixed and supply air conditions. The potential energy savings are independent on the zone load ratio. Figure 7 presents the potential energy savings ratios versus the nighttime airflow ratio for dual duct constant air volume terminal boxes under the following conditions: (1) the hot air temperature is 38°C (100 °F); and (2) both mixed air and cold air conditions are the same of the design conditions. If the airflow ratio is set at 30% during unoccupied hours, the thermal energy savings ratio is 0.88, which includes 0.39 for heating and 0.49 for cooling.

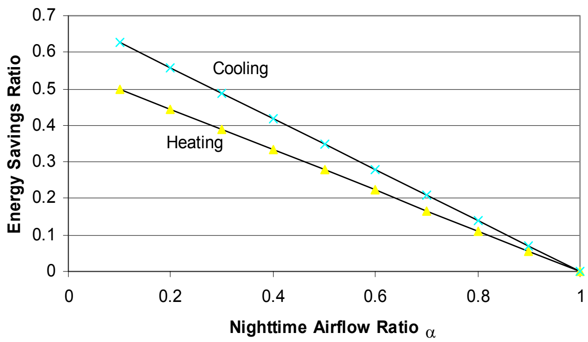

Figure 7: Cooling and Heating Energy Savings Ratio Versus the Airflow Reset Ratio for Dual Duct Constant Air Volume Terminal Boxes

Variable Air Volume Dual Duct Terminal Box

Figure 8 presents the airflow reset schedule for dual duct variable air volume terminal boxes. The daytime schedule has a minimum airflow ratio of α_1. The nighttime schedule has a minimum airflow ratio of α_2. During unoccupied hours, the airflow reset uses the nighttime schedule. During occupied hours, the airflow reset uses the daytime schedule. The standard schedule uses the daytime schedule all the times.

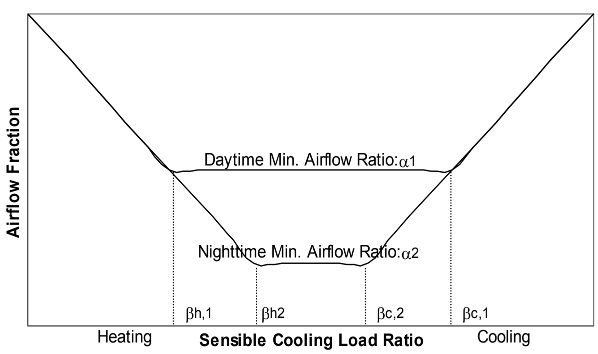

Figure 8: Airflow Reset Schedule for Dual Duct Variable Air Volume Terminal Boxes

When the zone load ratio is between $\beta_{c,2}$ and $\beta_{c,1}$, or between $\beta_{h,1}$ and $\beta_{h,2}$, the terminal box supplies either the hot air or the cold air to the zone using the airflow reset schedule. When the zone load ratio is between $\beta_{h,2}$ and $\beta_{c,2}$, the terminal box supplies the minimum air (α_2 fraction of the design airflow) to the zone. If both the mixed and the supply conditions are the same for both the airflow reset and the standard schedules, the potential heating and cooling energy savings ratios can be determined using Equations 13 and 14.

$$\eta_h = \begin{cases} \alpha_1 \dfrac{\beta_{c,1}-\beta}{\beta_{c,1}-\beta_{h,1}} \dfrac{t_h - t_m}{t_r - t_{c,d}} & \beta_{c,2} \le \beta \le \beta_{c,1} \\ \left(\alpha_1 \dfrac{\beta_{c,1}-\beta}{\beta_{c,1}-\beta_{h,1}} - \alpha_2 \dfrac{\beta_{c,2}-\beta}{\beta_{c,2}-\beta_{h,2}}\right) \dfrac{t_h - t_m}{t_r - t_{c,d}} & \beta_{h,2} \le \beta \le \beta_{c,2} \\ \alpha_1 \dfrac{\beta_{c,1}}{\beta_{h,1}} \dfrac{\beta_{h,1}-\beta}{\beta_{c,1}-\beta_{h,1}} \dfrac{t_h - t_m}{t_r - t_{c,d}} & \beta_{h,1} \le \beta \le \beta_{h,2} \end{cases} \tag{13}$$

$$\eta_c = \begin{cases} \alpha_1 \dfrac{\beta_{h,1}}{\beta_{c,1}} \dfrac{\beta-\beta_{c,1}}{\beta_{c,1}-\beta_{h,1}} \dfrac{h_m - h_c}{C_p\left(t_r - t_{c,d}\right)} & \beta_{c,2} \le \beta \le \beta_{c,1} \\ \left(\alpha_1 \dfrac{\beta-\beta_{h,1}}{\beta_{c,1}-\beta_{h,1}} - \alpha_2 \dfrac{\beta-\beta_{h,2}}{\beta_{c,2}-\beta_{h,2}}\right) \dfrac{h_m - h_c}{C_p\left(t_r - t_{c,d}\right)} & \beta_{h,2} \le \beta \le \beta_{c,2} \\ \alpha_1 \dfrac{\beta-\beta_{h,1}}{\beta_{c,1}-\beta_{h,1}} \dfrac{h_m - h_c}{C_p\left(t_r - t_{c,d}\right)} & \beta_{h,1} \le \beta \le \beta_{h,2} \end{cases} \tag{14}$$

Where:

$$\beta_{c,1} = \alpha_1 \frac{t_r - t_c}{t_r - t_{c,d}} \tag{15}$$

$$\beta_{h,1} = \alpha_1 \frac{t_r - t_h}{t_r - t_{c,d}} \tag{16}$$

$$\beta_{c,2} = \alpha_2 \frac{t_r - t_c}{t_r - t_{c,d}} \tag{17}$$

$$\beta_{h,2} = \alpha_2 \frac{t_r - t_h}{t_r - t_{c,d}} \tag{18}$$

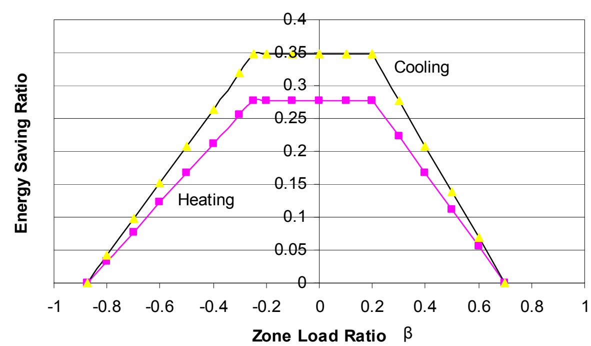

Figure 9: Potential Heating and Cooling Energy Savings Versus the Zone Load Ratio for Dual Duct Variable Air Volume Terminal Boxes

The potential energy savings ratios depend on the minimum airflow ratios, the zone load ratio, and the mixed and supply air conditions. Figure 9 presents the potential heating and cooling energy savings ratios versus the zone load ratio for dual duct variable air volume terminal boxes under the following conditions: (1) the minimum airflow ratios are 0.7 for the standard schedule and 0.2 for the airflow reset schedule; (2) the hot air temperature is 38°C (100°F); (3) both the mixed air and the room air temperature are 24°C (75°F); (4) the cold air temperature is 13°C (55°F); and (5) the mixed air enthalpy is same as the room air enthalpy. When the load ratio is between $\beta_{h,2}$ and $\beta_{c,2}$, the energy savings ratios are 0.35 for cooling and 0.28 for heating. The total potential energy savings are 0.63.

IMPLEMENTATION

The airflow reset uses a lower or zero minimum airflow for variable air volume terminal boxes and a lower airflow value for constant air volume terminal boxes. It decreases or eliminates simultaneous heating and cooling. The critical decisions involved in the airflow reset are the time period and the minimum airflow rate.

For VAV terminal boxes, the reset period can start right after the office hours and end right before the office hours. For CV terminal boxes, the reset period should start one or two hours after the office hours and end one or two hours before the office hours. This will allow using lower nighttime airflow rate.

The selection of the minimum airflow ratio should consider the following factors: zone ventilation requirements of occupants during unoccupied hours, zone odors, air stagnation, and zone exhaust airflow. For CV terminal boxes, the maximum potential zone load during unoccupied hours must be considered.

The airflow reset may be implemented using the terminal box controller only. However, central control systems may have to be used for most of the existing control systems. One method is to develop two control schedules (occupied and unoccupied). Based on the time, the central control system automatically switch between two schedules. (downloads the un-occupied schedule to the terminal box controller at the beginning of the unoccupied hours, and downloads the occupied schedule to the terminal controller at the beginning of the daytime hours.)

In 1997, the airflow reset was implemented in a dual duct variable air volume system in Houston, Texas. The AHU had 45 terminal boxes with a 40 hp supply air fan. The design airflow was 9.3 m^3/s (19,650 CFM). The occupied hours were from 8:00 a.m. to 7:00 p.m., Monday to Friday.

The standard schedule had minimum airflows from 40% to 70% with an average of 60% for different boxes. The airflow reset changed the minimum airflow to 20% for all boxes. The non-zero minimum airflow was used to maintain building pressure level.

The airflow reset was implemented on the last week of September 1997. The hourly ambient temperature, the variable frequency drive (VFD) speed, and the static pressure set point were recorded from August 1 to November 25 using the building automation system.

Figure 10 presents the recorded static pressure set point versus the variable frequency drive speed during the unoccupied period. The static pressure set point decreases with the VFD speed when it is higher than 60%. When the VFD speed is lower than 60%, the static pressure remains at 125 Pa (0.5 inH_2O).

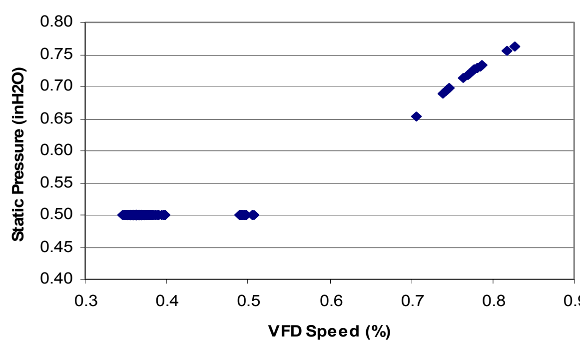

Figure 10: Recorded Hourly Average Static Pressure Set Point Versus the VFD Speed During the Unoccupied Hours

Figure 11 presents the recorded VFD speed versus the ambient temperature during the unoccupied hours. Before the implementation of the airflow reset (August 1 to September 23), the VFD speed was approximately 60%. After the implementation (October 1 to November 25), the VFD speed was approximately 37%.

The airflow rate was determined using the measured VFD speed, the fan design working point, the static pressure set point and the fan curve. Figure 12 compares the measured airflow before and after the airflow reset during the unoccupied hours. Before the airflow reset, the airflow ratio varied from 60% to 70% during the unoccupied hours. After the implementation of the airflow reset, the airflow ratio varied from 17% to 30%. The airflow reset decreased airflow by 40% of the design flow during the unoccupied hours

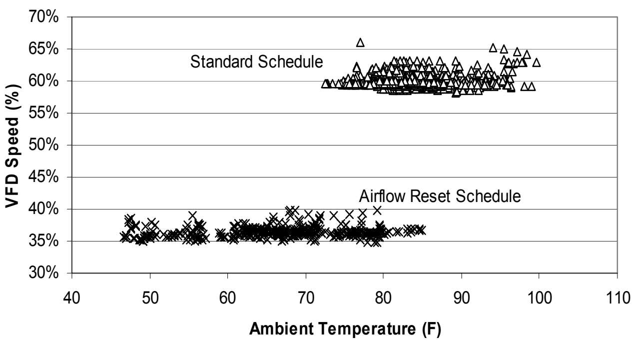

Figure 11: Measured Fan Speeds Before and After Implementation of the Airflow Reset During Unoccupied Hours

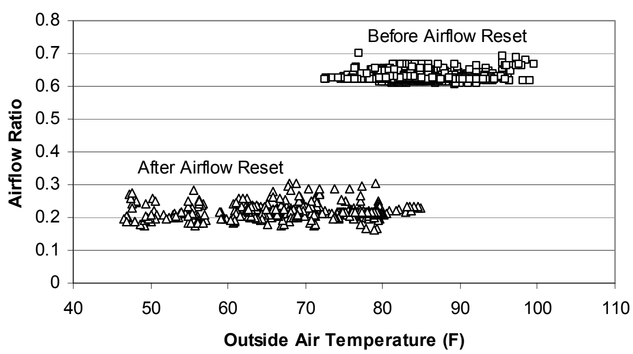

Figure 12: Comparison of the Measured Airflow Ratios Before and After the Airflow Reset During the Unoccupied Hours

CONCLUSIONS

The airflow reset decreases the minimum airflow for VAV terminal boxes and reduces the total airflow for the constant air volume terminal boxes during unoccupied hours. Terminal boxes and AHUs consume considerable less heating, cooling and fan power and maintain room temperature at the daytime set point when the airflow reset is used. A case study measured 40% of design airflow reduction in AHU level.

The reset value of airflow reset should be determined based on the maximum potential load ratio and the exhaust airflow ratio or zone pressure control level for a constant airflow terminal box. A nonzero airflow may also be required for a variable air volume terminal box due to building pressurization requirements.

NOMENCLATURES

cp – Air specific heat (J/kg°C, or Btu/lbm°F)

h – Enthalpy (J/kg, Btu/lbm), fan head (Pa, or inH_2O)

p – Pressure loss, pressure (Pa, or inH_2O)

E – Energy consumption (W or Btu/hr)

Q – Airflow rate (m^3/s or CFM)

T – Temperature (°C or °F)

α - Airflow ratio

β - Zone sensible cooling load ratio

η - Energy savings ratio (energy savings over the design sensible cooling load)

λ - Airflow reduction ratio (Airflow reduction over the design airflow)

φ - VFD speed

Subscripts

c – cold air, cooling

d - design

h – hot air, heating

o - occupied

m – mixed air

min - minimum

r - zone

rh – re-heat

s – set point, supply air

u – unoccupied, lightly occupied

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