A Novel Procedure to Determine Optimal Air Static Pressure Set-points and Reset Schedules in VAV Air Handling Units

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ABSTRACT

Air static pressure set-point or schedule for VAV AHU systems is one of the most crucial operational parameters for satisfying the building load, maintaining the room comfort level and saving energy costs. This paper presents a novel procedure and method, which can be applied to determine the optimal air static pressure set-point for VAV AHUs with both stand-alone controllers and DDC controllers. This procedure provides a simple, fast and a non-intrusive way to obtain the optimal or improved operational schedules without interrupting normal operation of the systems and without detailed simulation. An application example is also presented in this paper.

INTRODUCTION

The air static pressure, normally refers to the air static pressure at 2/3 of the distance down stream from the air handing unit where the static pressure sensor is located. Air static pressure must be maintained at a certain level to force a suitable amount of air through the air distribution duct and other components, such as the damper, terminal boxes and diffusers. The air static pressure is normally maintained by modulating the VFD speed of the fan and in some cases by adjusting the inlet guide vanes in VAV systems. The controllers for the VFD as well as inlet guide vanes are classified as two types: DDC control and stand-alone control. The set-point or schedule of air static pressure for VAV AHUs is one of the most crucial operational parameters for satisfying the building load, saving energy costs, improving room comfort level as well as the noise level in some cases. The impacts of the air static pressure set level on the HVAC system energy consumption and indoor conditions have been investigated [Liu, Zhu and Claridge, 1996; Warren and Norford, 1993]. Implementation of the improved air static pressure set-points or schedules can greatly benefit the energy savings

of the HVAC systems [Zhu, Liu and Claridge, 1997; Rose and Kopko, 1994]. The optimal set-point of air static pressure is often obtained either through the simulations, or by engineering experiences. However, these methods are either time consuming or they ignore real conditions of special systems.

During building commissioning processes, the authors have developed a novel method which can determine the optimal air static pressure set-point without interrupting normal operation and with minimum field measurements. This paper presents the method and an application example.

METHOD

The key to this new method is to identify the basic fluid characteristics by combining fundamental theories and basic field measurements.

The general method is presented in the following with the example of a dual duct dual fan AHU system shown in Figure 1.
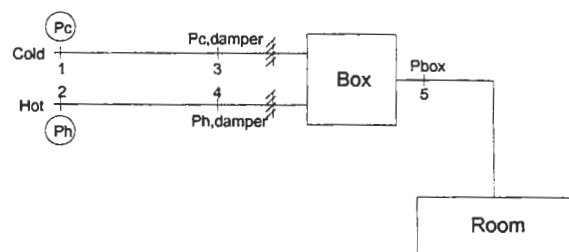

Figure 1. Diagram of the typical VAV box and duct of a dual duct dual fan AHU system

The basic principle is that the optimal static pressure set-point SP_{op} equals to the minimum required static pressure drop from the sensor location to the diffuser under the operational load ratio considering the real condition of the system. The basic equation is as follows:

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$$SP_{op} = \Delta P_{box} + \Delta P_{damper} + \Delta P_{duct} \qquad (1)$$

where ΔP_{box} is the minimum static pressure drop from the box to the room diffuser under operational box load condition; ΔP_{damper} is the minimum static pressure drop for the box damper under operational box load condition or under operational cold or hot duct flow condition; ΔP_{duct} is the minimum duct static pressure drop from the static pressure sensor location of 1 or 2 to box damper 3 or 4 under operational zones load condition.

For AHUs with DDC controllers, the optimal reset schedule can be reset according to the operational load ratio.

For AHUs with stand-alone controllers, the optimal schedule may only have two values, one for summer weather, one for winter weather because the controller is often incapable of changing the set-point automatically. In order to satisfy the maximum cooling or heating load condition with a single optimal set-point, the optimal set-point must be obtained in two steps: obtain minimum required value under measured condition and calculate optimal set-point with assumption of the peak load condition. In normal cases, we assumed turbulent flow, when the optimal reset schedule is determined.

The following discusses the method and equations for different kinds of AHUs with both stand-alone controller and centralized control systems.

DDVAV AHU-Dual Fan with Stand-alone Controller (DDDFVAV-SC)
Normally, the system has two static pressure sensors in the duct with two set-points. The VFD for hot deck and cold deck fans are controlled separately. Figure 1 is the typical diagram for DDVAV system.

Step 1: Field Measurements and Inspections
The method requires to measure the static pressures (P_c & P_h in the main duct; $P_{c, damper}$, $P_{h, damper}$ and P_{box} for the far-end box). The basic load ratio of the far-end box and zones served by the unit need to be inspected or flow rate needs to be measured.

Step 2: Summer Schedules:
Determination of the optimal cold air static pressure set-point:
From the basic field measured results and inspections, the optimal cold air static pressure set-point for an AHU is obtained using equation (2):

$$P_{csp} = P_{box} \left[\frac{1}{\beta_{boxmeas}} \right]^2 + \Delta P_{damper}$$
$$+ (P_c - P_{c,damper}) \left[\frac{1}{\beta_{duct}} \right]^2 \qquad (2)$$

where P_{box} is the measured static pressure after box; ΔP_{damper} is the minimum required static pressure drop for the box cooling damper under peak cold air flow (normally 0.2 or 0.3"H$_2$O); $P_c - P_{c, damper}$ is the measured static pressure drop from the cold air duct static pressure sensor location to the box damper location; $\beta_{boxmeas}$ is the estimated cooling load ratio for the box (the area served by this box is under what level of cooling load condition) under measured condition and β_{duct} is the cooling load ratio of the AHU under measured conditions.
Determination of the optimal hot air static pressure set-point
First, the minimum air flow rate of the AHU is calculated by equation (3):
$$CFM_{min} = A\,Q \qquad (3)$$
where A is the conditioned area served by the unit, sq-ft; Q is often considered to be 0.3 or 0.4 CFM/sq-ft to maintain suitable air circulation.

If the CFM$_{min}$ is less than the measured cold air flow CFM$_{c1}$, there is often no need to have hot air flow for comfort purposes. To reduce the hot air flow to the minimum, the hot air static pressure should prevent cold air from flowing back through the hot air duct and provide hot air in case it is needed in some areas. The minimum hot air static pressure set-point is determined using equation (4):

$$P_{hsp} = P_{box} \left[\frac{1}{\beta_{boxmeas}} \right]^2 \qquad (4)$$

If the CFM$_{min}$ is more than the measured cold air flow CFM$_{c1}$ for the AHU, the cold air temperature T_{c1} should be checked first. If T_{c1} can be increased to T_{c2} within the reasonable room RH level (e.g. 57%), the CFM$_{c2}$ will be :

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$$CFM_{c2} = \frac{(T_r - T_{c1})\, CFM_{c1}}{(T_r - T_{c2})} \qquad (3')$$

If the CFM_{min} is less than the cold air flow CFM_{c2} then the minimum hot air static pressure set-point is determined using equation (4).

If the CFM_{min} is still more than the cold air flow CFM_{c2}, the hot air is needed at least for circulation purposes. The optimal hot air static pressure set-point for AHUs is then obtained using equation (5):

$$P_{hsp} = P_{box} \left[\frac{1}{\beta_{boxmeas}} \right]^2 + \Delta P_{damper}$$

$$+ (P_h - P_{h, damper}) \left[\frac{CFM_{min} - CFM_c}{CFM_h} \right]^2$$

$$(5)$$

where $P_{box} \left[\dfrac{1}{\beta_{boxmeas}} \right]^2$ is the same as (2);

ΔP_{damper} is the minimum required static pressure drop for the box heating damper under full open condition (normally 0.2 or 0.3"H_2O); P_h - $P_{h, damper}$ is the static pressure drop from the hot air duct static pressure sensor location to the box damper location under the measured conditions; CFM_c and CFM_h are the measured cold and hot air flow of the AHU.

Step 3: Winter Schedules:
Determination of the optimal cold air static pressure set-point:

From the field measured results and inspections, the optimal cold air static pressure set-point is obtained using equation (6):

$$P_{csp} = P_{box} \left[\frac{1}{\beta_{boxmeas}} \right]^2 + \Delta P_{damper} +$$

$$(P_c - P_{c, damper}) \left[\frac{\beta_c}{\beta_{duct}} \right]^2 \qquad (6)$$

where P_{box} is the measured static pressure after box; ΔP_{damper} is the minimum required static pressure drop for the box cooling damper under peak cold air flow (normally 0.2 or 0.3"H_2O); P_c - $P_{c, damper}$ is the static pressure drop from the cold air static pressure sensor location to the boxes damper location under measured

conditions; $\beta_{boxmeas}$ and β_{duct} are the estimated cooling load ratios for the box and the zones served by this unit under the measured conditions; β_c is the estimated maximum cooling load ratio for the unit in the winter weather time.

Determination of the optimal hot air static pressure set-point

$$P_{hsp} = P_{box} \left[\frac{1}{\beta_{boxmeas}} \right]^2 + \Delta P_{damper}$$

$$+ (P_h - P_{h, damper}) \left[\frac{1}{\beta_{duct}} \right]^2 \qquad (7)$$

where $P_{box} \left[\dfrac{1}{\beta_{boxmeas}} \right]^2$ is the same as (2);

ΔP_{damper} is the minimum required static pressure drop for the box heating damper under full open conditions (normally 0.2 or 0.3"H_2O); P_h - $P_{h, damper}$ is the static pressure drop from the hot air duct static pressure sensor location to the box damper location under the measured conditions; β_{duct} is the estimated heating load ratios for the zones served by this unit under the measured conditions.

DDVAV AHU-Single Fan with Stand-alone Controller (DDVAV-SC)
Normally, the system has two sensors located in the cold air and hot air ducts respectively. The minimum air static pressure is used to control the VFD. The VAV box and duct diagram can be seen in Figure 1.

Step 1: Field Measurements and Inspections
The method requires to measure the static pressures (P_c, P_h at the main duct, $P_{c, damper}$, $P_{h, damper}$ and P_{box} for the far-end box). The basic load ratio of the far-end box and zones served by the unit needs to be inspected or flow rate needs to be measured.

Step 2: Summer Schedules:
Based on the basic measured results, the summer air static pressure set-point is obtained using equation (2).

Step 3: Winter Schedules:
The initial static pressure set-point can be calculated by equation (6) and (7) first. The

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winter set-point is then determined by equation (8):

$$P = \max\{P_{csp}, P_{hsp}\} \qquad (8)$$

SDVAV AHU with Stand-alone Controller (SDVAV-SC)

Figure 2 shows the diagram of the measured box and duct.
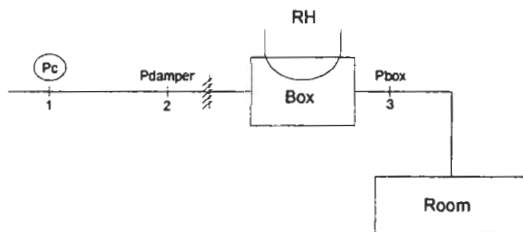

Figure 2. Diagram of the duct and box for SDVAV system

Step 1: Field Measurements and Inspections
The method requires to measure the static pressure P_c (at the sensor location 1,); P_{damper} and P_{box} for the far-end box. The basic load ratio of the far-end box and zones served by the unit needs to be inspected or flow rate needs to be measured.

Step 2: Summer and Winter Schedules:
The static pressure set-points are determined by equation (2) and (6) for summer and winter respectively.

DDVAV - Dual Fan AHU with DDC Controller (DDDFVAV-DDC)
The DDC controller has the capability to reset the air static pressure schedules based on the building load conditions which include air flow rate of the unit, fan speed, VFD PID loop output and outside air dry bulb temperature. The optimal schedules for the system with DDC controller can also have the low and high limits.

A DDDFVAV system has two static pressure sensors. The VFD for hot deck and cold deck fans are controlled separately. Figure 1 shows the diagram of the box and duct.

Step 1: Field Measurements and Inspections
The method requires to measure the static pressures (P_c , P_h at the sensor location, 1 for cold and 2 for hot duct; $P_{c, damper}$, $P_{h, damper}$ and P_{box} for the far-end box). The load ratio of the far-end box and zones served by the unit needs

to be inspected or flow rate needs to be measured.

Step 2: The air duct flow resistance coefficient S
Take the cooling duct as an example. If the control system has the flow station CFM or has the VFD speed SPD or has the VFD PID loop output V, then the static pressure can be reset based on one of these factors. Assume the flow rate CFM_{mean} can be measured by EMCS DDC system, then the S will be:

$$S = \frac{P_c - P_{c, damper}}{\left(CFM_{mea}\right)^2} \qquad (9)$$

Step 3: Determine the optimal air static pressure reset schedules SP_{op}
If the EMCS monitored air flow CFM, then SP_{op} will be:

$$SP_{op} = S\,(CFM_{new})^2 + P_{box}\,[\frac{1}{\beta_{boxmeas}}]^2$$
$$+ \Delta P_{damper} \qquad (10)$$

$$SP_{op} = SP_{lo} \quad \text{If } SP_{op} < SP_{lo} \qquad (10')$$
$$SP_{op} = SP_{hi} \quad \text{If } SP_{op} > SP_{hi} \qquad (10'')$$

The flow may be laminar flow when the flow rate is too low. So, the low limit SP_{lo} has to be used. The high limit SP_{hi} will prevent unnecessary pressurization in case failure of sensors.

If the EMCS does not monitor air flow CFM, but can record the fan speed SPD or VFD PID loop output V, then SP_{op} will be:

Obtain S and SP_{op} through (9), (10), (10') and (10'') by using SPD or V instead of CFM. Calculate 3 or 4 SP_{op} values through hand calculations within the value of SP_{lo} and $SP_{hi,}$. Then, the optimal reset schedules will be 3 or 4 step values based on a range of SPD or V, but not a linear relation.

If the EMCS does not monitor air flow CFM, does not record the fan speed or VFD PID loop output V, then SP_{op} will be:

Correlate the SP_{lo}, SP_{hi} with the outside air temperature. Linear equations may be used.

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Since the cooling load increases while the heating load decreases as the outside air temperature increases.

For step 2 and step 3, the hot air static pressure reset schedule can be determined by using the same procedure.

Step 4: Determine SP_{lo} and SP_{hi} for the cold deck fan

The highest limit SP_{hi} of the static pressure is determined by equation (2).

When the flow is low or laminar flow, the pressure drop changes linearly with the flow rate. Equation (10) may produce a unrealistic low static pressure set-point at low flow rate due to the assumption of turbulent flow. Therefore a low limit is needed. We suggest a low limit of $0.3"H_2O$.

Step 5: Determine SP_{lo} and SP_{hi} for the hot deck fan

The highest limit SP_{hi} of the static pressure is determined by equation (7).

The lowest limit SP_{lo} of the static pressure is suggested to be $0.3"H_2O$.

DDVAV - Single Fan AHU with DDC Controller (DDVAV-DDC)

Figure 1 shows the diagram of the measured box and duct.

Steps 1 to 3 are the same as *DDDFVAV-DDC*.

Step 4: Determine SP_{lo} and Sp_{hi}

The highest limit SP_{hi} of the static pressure is determined by equation (2).

The lowest limit SP_{lo} of the static pressure is suggested to be $0.3"H_2O$.

SDVAV AHU with DDC Controller (SDVAV-DDC)

Figure 2 shows the diagram of the measured box and duct.

Steps 1 to 4 are the same as *DDVAV-DDC*.

Other Important Issues Related with New Optimal Reset Schedules or New Set-points

We suggest to verify the pressure readings of EMCS sensors by using the hand meters. If the control system readings do not agree with the hand meter readings, repair or replacement should be performed. If a systematic bias exists, a " soft correction" may be used. After the new set-point or reset schedules have been implemented and enabled, fine tuning of the schedules may be needed. If comfort problems occur in some area, correct the problems by trouble shooting the individual box and flex duct or other flow components first, then consider fine tuning the new schedules.

APPLICATION
Building and HVAC System Information

The building is a four story university teaching building with approximately 141,000 sq-ft of conditioned area. Eight DDDFVAV AHUs serve this building. The AHUs only allow the return air to pass through the hot air duct, and mixed air to pass through the cold air duct. Stand-alone controllers are used to control the VFD of the cold deck, hot deck fans and deck temperatures. Figure 3 shows the diagram of the AHUs. Table 1 summarizes the AHU operation conditions before the commissioning.

The cold air static pressure set-points varied from $0.8"H_2O$ to $1.2"H_2O$ and hot duct static pressure set-points varied from $0.43"H_2O$ to $0.8"H_2O$ for different AHUs during the site visit. The cold deck ranged from 52°F to 58°F and hot deck ranged from 76°F to 80°F based on measured results.

Optimal Control Schedules

From the measured results, an analysis identified the following opportunities:

  (1) Reduce the hot air flow to the building in the summer time by optimizing hot duct static pressure set-points.
  (2) Optimize the cold duct static pressure set-points.
  (3) Optimize the cold/hot deck temperature set-points.

Summer Schedules

Based on the measured results, it was found that CFM_{min} was less than the measured cold air flow for all the AHUs. The optimal air static pressure set-points were determined by equations (2) and (4).

Winter Schedules

Using equations (6) and (7), the cold and hot duct air static pressure set-points under winter weather conditions were obtained.

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Table 1: Summary of the AHU Operations before Commissioning (Toa: 85°F to 94°F)

AHU	Mixed Air (°F)	CD (°F)	RA (°F)	HD (°F)	Pc* (Static)	Ph* (Static)	CD VFD%	HD VFD%	RF VFD%
1N	77.5	56.8	73.7	80.3	0.85"	0.6"	60	41	38
1S	75.6	56	78	80	1.2"	0.8"	67	50	47
2N	76.5	58.2	76	76.5	0.9"	0.43"	75	66	46
2S	77.4	51.5	76.4	78.5	1.0"	0.6"	53	90	15
3N	77.4	54.3	74.6	79.1	0.8"	0.6"	72	71	9.5
3S	81.6	54.7	75.3	76.4	1.17"	0.7"	75	47	37.2
4N	78.6	55.4	77.2	77.6	0.95"	0.6"	54	46	8.6
4S	75.9	55.7	74.9	77.3	1.0"	0.45"	40.6	43	39
Ave.	77.5	55.3	75.8	78.2	0.98"	0.6"	62	57	30

*: Readings where the static pressure was measured by the duct static pressure sensor located approximately 2/3 of the length of the main duct from the AHUs.
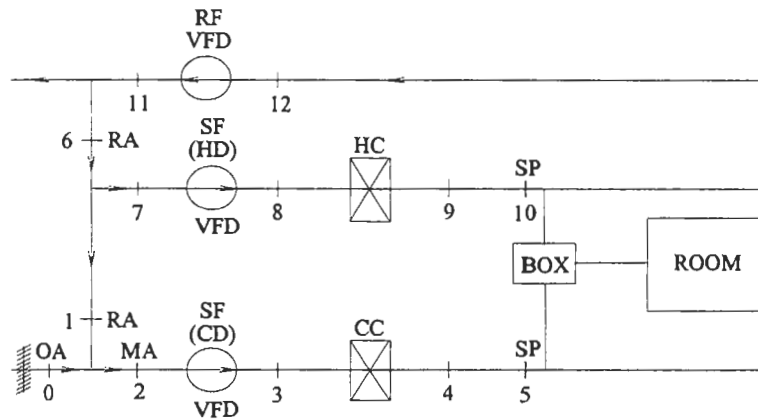

Figure 3. Diagram of the AHUs

Table 2 summarizes the optimal set-points for AHUs.

Measured Results

The commissioning suggestions for both static pressure set-points and cold/hot deck temperature set-points were implemented on June, 1997.

Before the implementation of optimal schedules, the average room temperatures varied from 70.2°F to 72.7°F with relative humidity levels ranging from 55% to 62.3%. After the implementation, the room temperatures are in a range of 70.6°F to 73.1°F with relative humidity levels ranging from 55% to 59.8%.

During the summer vacation period, the electricity consumption was reduced by an average of about 10 kWh/hr or 20% of the fans and pumps electricity usage, the cooling and heating energy consumption were also reduced by an average of about 0.2 & 0.3 MMBtu/hr.

During the fall semester with full scale of occupancy, the electricity consumption was reduced by an average of about 7 kWh/hr or 15% of fan and pumps electricity usage, the cooling and heating energy consumption were also reduced by an average of about 0.15 & 0.3 MMBtu/hr. The annual estimated energy cost savings will be over $15,000 based on the energy prices of $0.03483/kWh for electricity, $3.25/MMBtu for chilled water and $3.45/MMBtu for steam. Figures 4 to 9 show the energy consumption reduction through the commissioning.

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Table 2-1. Summary of the Optimal Set-points for All AHUs except AHU-1S

Item	CD Fan CDP$_c$ ("H$_2$O)	HD Fan HDP$_h$("H$_2$O)	CD Temp. CDT (°F)	HD Temp. HDT (°F)
Summer	0.6	0.2	57	Shut off heating coils
Winter	0.4	0.4	58	89 @<30 of OAT, 72 @ >65 OAT

Table 2-2. Summary of the Optimal Set-points for AHU-1S

Item	CD Fan CDP$_c$ ("H$_2$O)	HD Fan HDP$_h$ ("H$_2$O)	CD Temp. CDT (°F)	HD Temp. HDT (°F)
Summer	1.2	0.2	57	Shut off heating coils
Winter	0.4	0.4	58	89 @<30 of OAT, 72 @ >65 OAT

Note: A hot spot in one room for AHU-1S is due to higher heat gain through the roof in summer. If the insulated ceiling is added, the set-point will be the same as the others.
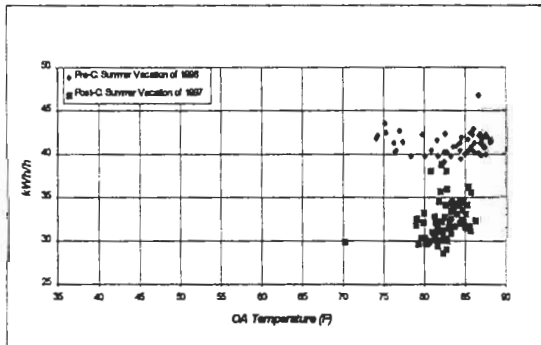
Figure 4. Comparison of daily average electricity consumption of fans & pumps before and after commissioning during the summer vacation period
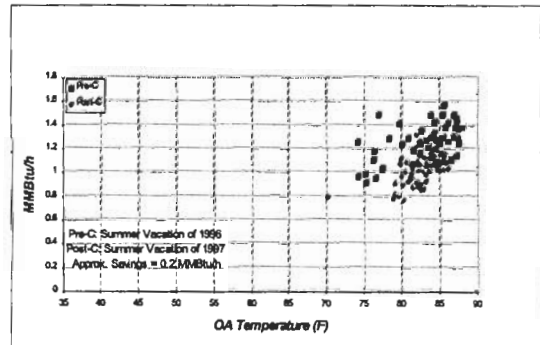

Figure 6. Comparison of daily average chilled water consumption before and after commissioning during the summer vacation period
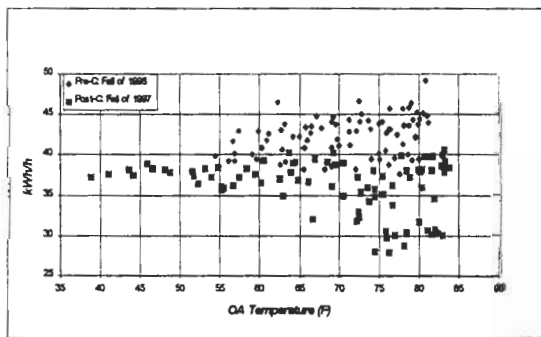

Figure 5. Comparison of daily average electricity consumption of fans & pumps before and after commissioning during the fall semester
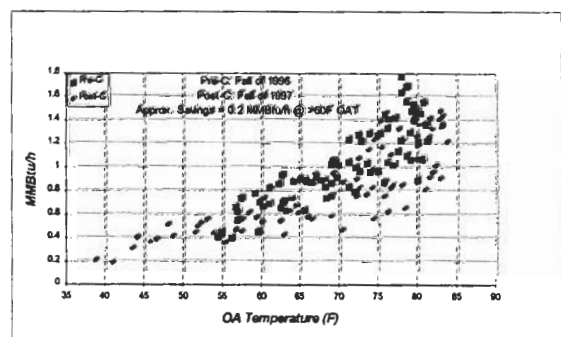

Figure 7. Comparison of daily average chilled water consumption before and after commissioning during the fall semester period

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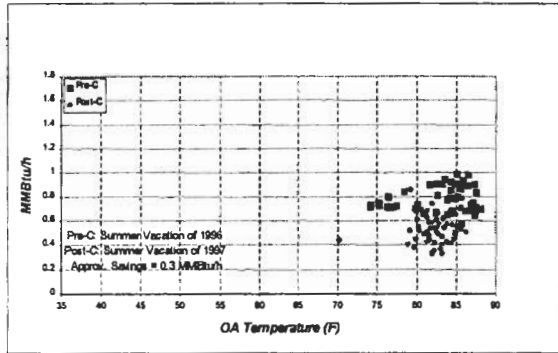
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Figure 8. Comparison of daily average steam consumption before and after commissioning during the summer vacation period
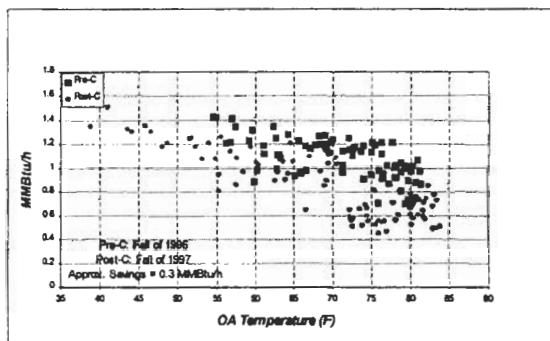

Figure 9. Comparison of daily average steam consumption before and after commissioning during the fall semester period

CONCLUSION

A novel procedure for optimizing the air static pressure set-points of VAV AHUs has been developed. It is a non-intrusive method to obtain the optimal or improved air static pressure set-points. It also needs minimum measurement due to combining the minimum measurements with EMCS data. This procedure considers the real operational condition of the systems and eliminates the detailed simulation for this purpose. It can be used by commissioning engineers and facility engineers.

ACKNOWLEDGMENTS

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